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*At 18,734 feet,**

on The Superior Oil Company

world's record depth well,

Schlumberger made an electrical

log in 3½ hours hole time.

Schlumberger made two runs below 18,000' on The Superior Oil Company's Limoneira No. 1, the new world's record depth well. The first run was made at 18,110 feet and the second on March 13, 1949, at 18,734 feet. Both operations were carried out successfully as routine runs with regular Schlumberger surveying equipment and with a minimum of rig time. Only 3½ hours surveying time was required for each run. Performance of Schlumberger equipment on this new world's record well is proof again that Schlumberger is ready now for your 20,000 foot, or deeper, wells.

*Schlumberger has since logged the Superior Oil Company's Pacific Creek No. 1 — the new record depth well in Wyoming — to 18,704 feet.

SCHLUMBERGER
WELL SURVEYING CORP.
HOUSTON, TEXAS

Yes . . .

We Sincerely Recommend That You Vote and Vote YES

LLOYD E. ELKINS

PETROLEUM BRANCH CHAIRMAN

On the first page of the All-Institute Section of this issue, President L. E. Young presents the recommendation of the Local Section Delegates, and of the Board of Directors, that dues be increased $5.00 for Members and Associate Members, and $2.00 for Junior Members, to be effective in 1950 and to carry through 1952, with provision for referendum in 1952 to determine the dues level thereafter. This recommendation will be voted upon by all members living in the U. S., Canada, and Mexico. Your ballot should reach you within two weeks.

The Petroleum Branch Executive Committee, being convinced that all sound approaches to another solution have been tried, and in view of the stipulation that the dues must be redetermined by the membership in 1952, *adds its recommendation that you vote to approve the increase in dues.*

In determining the justification for a raise in dues our first step was to obtain a financial statement that clearly set out the financial position of each Branch. This statement appears here as the Institute Budget for 1949. We have carefully scrutinized the accounting procedures now in use in handling Branch accounts and,

AIME BUDGET FOR 1949

(Based on Operations of First Quarter)

INCOME	Petroleum Branch	Metals Branch	Mining Branch	Entire Institute
*Dues and Initiation Fees	$ 58,279	$ 58,284	$121,937	$238,500
Advertising in Branch Journals	20,000	15,000	55,000	90,000
Sales of Journals and Transactions	11,500	13,500	16,000	41,000
Doherty Fund Contribution	5,000			5,000
*Interest on Funds	1,369	1,415	3,065	5,849
TOTAL INCOME	$ 96,148	$ 88,199	$196,002	$380,349
EXPENSE				
Transactions and Special Volumes	$ 17,613	$ 8,452	$ 13,719	$ 39,784
Branch Journals[1]	38,868	99,218	89,047	245,133
Branch Expense[2] (except Journals)	18,000			
*Meetings[3]	4,840	4,340	9,320	18,500
*Local Section Appropriations	5,730	3,580	5,690	15,000
*Engineering Societies Library	1,421	1,469	3,182	6,072
Proration of New York Office Expense:				
*Office Rent	2,330	2,410	5,255	9,995
*Administrative, Accounting & Membership Depts.[4]	22,692	22,391	45,805	90,888
*Pension Fund	2,808	2,904	6,288	12,000
TOTAL EXPENSE	$114,302	$144,764	$178,306	$437,372
TOTAL INCOME	96,148	88,199	196,002	380,349
OPERATING DEFICIT or SURPLUS	$ 18,154	$ 56,565	$ 17,696	$ 57,023 [5]

* Designates items which are involved in the operation of the Institute overall, with no more application to one Branch than to another. These items have been distributed to the Branches in proportion to the relative membership strength of the Branch, i.e., Petroleum 23.4%; Metals 24.2%, and Mining 52.4%, with minor adjustments in some cases to cover special circumstances.

[1] Includes cost of production and distribution as well as office rent, salaries and other overhead, and includes All-Institute Section as well as Branch Sections.

[2] Includes all Dallas salaries, rent and other overhead not properly chargeable to the Journal.

[3] Charge against Petroleum Branch includes $1,000 provided to us by Institute for Fall Meetings. Balance of $3,840 represents prorated charge for cost of AIME Annual and Regional Meetings.

[4] Includes salaries paid to all N. Y. office personnel not assigned to a particular Branch, also expense for supplies, equipment, telephone, etc., and national secretary's traveling expense.

[5] Because of $8,500 received as voluntary contributions from members, the actual 1949 deficit is expected to be $48,500.

although not yet perfect, it is concluded that for all practical purposes the figures thus developed are truly representative.

When this budget was before us we asked the questions we believed you would ask when the proposition came before you.

1. Is a raise in dues really necessary?

You will note that a deficit of $48,500 is expected from 1949 operations; moreover, deficits from the past few years, totalling $100,000, have had to be met by borrowing from all of the special funds that can be legally used to cover operating deficits. These funds are now depleted. The failure of the Institute to receive more income in 1950 could only mean a drastic reduction in membership services. It may be true that if some different pattern of operation had prevailed for the past several years the increase in dues would not be necessary. We must, however, face the condition that exists, not one that might have been.

The new publications plans has been the major move to avoid further deficits but since it was adopted only five months ago, long after matters had reached a crucial stage, it has not had opportunity to demonstrate its income potential. Even so the new program has promise of improving the Institute's position for 1949, as compared to 1948, by about $35,000. The 1948 net cost of "Mining & Metallurgy", the small "Technologys" and the Transactions volumes was $134,000 (total Institute deficit for 1948 — $82,000). The 1949 net cost of the three new journals and the Transactions is expected to be $100,000, so it can be said that an important step in the right direction has been taken. An increase in advertising revenue from the Journals is expected, and important economies in all phases of operation may be effected in the next few years, but the financial problem is now far too pressing to depend upon anything but the quickest means of increasing income. *A raise in dues is necessary.*

2. Will a raise in dues penalize the petroleum members for the activities of other Branches?

Since the Institute has instituted financial reporting by Branches, it is now easy to deal directly with this question.

You will note from the Budget that the Mining Branch, by virtue of large membership and consequent greater income from dues, is the only Branch that provides more money than its activities cost. The Petroleum Branch fails by $18,000 to support its own activities, and the Metals Branch position is even more conspicuous. It is clear that the Petroleum Branch is not now paying its way in the Institute.

To clarify the relationship of each class of petroleum member to the Institute's financial problems, we have broken costs and income down to a per-member level. This action provided some significant figures on the "average" petroleum member, who is a composite of all classes. The figures answer other pertinent questions, such as:

3. What income does each petroleum member bring to the Institute?

(Based on Budget for 1949)

Class of Petroleum Member	Number of Members	Dues	Initiation	Advertising in Jnl. Petr. Tech.	Sale of Transactions and Statistics Vols., and Journal Subscriptions	Doherty Fund Plus Interest on Other Funds	Total
Student Associate	850	$ 4.50	.....	$4.47	$2.59	$1.42	$12.98
Junior Members	897	10.00	.....	4.47	2.59	1.42	18.48
Members and Associate Members .	2,723	15.00	1.70	4.47	2.59	1.42	25.18
Average for all Classes Combined .	4,470	$12.00	$1.03	$4.47	$2.59	$1.42	$21.51

4. What does it cost the Institute to service a petroleum member?

(Based on Budget for 1949)

Class	Number of Members	New York Office and Library	Dallas Office General Activities	Jnl. of Petroleum Technology	Production of Transactions and Statistics Vols.	Meetings, Local Sec. Appropriations Delegates RR Fare	Total
All Classes Combined	4,470	$6.54	$4.02	$8.69	$3.49	$2.36	$25.55

5. How much must the Institute provide by deficit financing to carry the average petroleum member in 1949?

The table above answers the question. Average cost ($25.55) less average income ($21.51) = $4.04.

Calculated for each class of member, this deficit financing applies as follows:

	Cost of Service	Income	Deficit
Students Associate . . .	$25.55	$12.98	$12.57
Junior Member	25.55	18.48	7.07
Member and Associate . .	25.55	25.18	.37

6. How much will the raise in dues increase the Institute's income per average petroleum member in 1950?

Two thousand, seven hundred and twenty-three Members at an added $5.00 and 897 Junior Members at an added $2.00 will raise the average income per petroleum member, including students, by $3.44, or less than the indicated deficit. However, when this calculation is made for the total AIME membership the expected additional income equals the expected 1949 deficit. The proposed increase in dues is in the smallest amount that could be effective in getting the Institute back on a current basis.

7. If dues are raised, how much of a petroleum Member's dues will be available to subsidize Junior Members and Student Associates?

Since at the current dues level each Member provides in income 37c less than his service costs, the popular conception that he pays his own way and part of the younger member's is not true. However, under the proposed increase the Member, in providing $30.18 income as against service cost of $25.55, would provide $4.63 to aid in subsidizing Junior Members and Student Associates.

8. What are the prospects for reverting to the present dues level after the referendum of 1952?

All officials of the Institute are hopeful that developments of the next three years will enable them to ask you to vote to lower your dues effective with 1953. The Petroleum and Metals Journals will in the interim have proved themselves one way or another as a source of income. Each of these Journals is expected to have a revenue potential at least double the amount produced in their first year.

Apart from greater advertising income, the hope for a reversion to lower dues rests almost entirely in discovering changes in policy or procedure that will lower costs without impairing service. For example the Board of Directors, at our behest, has just resolved that all meetings (other than Local Section) will be made self-supporting, insofar as possible. Since Annual and Regional meetings have been costing the Institute several thousand dollars each year ($18,000 expected in 1949), the resulting saving will be appreciable. Your Executive Committee will watch developments as to these meetings and if necessary will press the Board to make the resolution iron-clad.

New York office overhead, and the library, have often been mentioned as at least partial cause of our money troubles, but most of those who have closely studied the matter have concluded that, under the existing general plan of operation, this overhead is not susceptible to important reduction by simple economy measures. The charge for the library and the space occupied in the building result from contracts with the other Founder Societies and the charter issued by the State of New York. These restrictions can only be dissolved by the courts, and at the probable disproportionate sacrifice of our share in the existing plant and the building replacement fund.

Salaries of the New York staff are not considered larger than need be paid to secure competent people and there is no evidence of waste of time or materials, or of extravagance — in fact, the contrary seems generally to be true. A study is now being made of the feasibility of centralizing the accounting and membership records systems of the Founder Societies in a machine-records unit. Apart from some hope of savings if this can be done it is not to be expected that New York overhead is open to drastic reduction without impairment of the accounting, membership promotion, and membership records services which it renders to all Branches.

We are mindful that the cost of Branch activities also looms large in the totals. Since you are in closer touch with these activities (Journal of Petroleum Technology, Transactions Volumes, Statistics Volume, Branch Meetings, assistance to Branch Committees and Local Sections) they will have more tangibility to you than the functions of the Institute office, which are actually just as essential to overall attainment of our objectives.

Again we urge you to express your willingness to help your Institute out of its difficulties by an affirmative vote on the raise in dues. In return we promise you that we will be vigilantly working for the elimination of all items of expense that do not have equivalent value to the petroleum membership, and will be alert to opportunities for increasing income. One way to improve the situation enormously is to increase membership total so that per-member costs will be much less. We realize that the raise in dues might slacken the flow of new members, but not, we believe, to an extent that cannot easily be overcome by vigorous action by the Branch and Local Section membership committees, and by all members as individual salesmen for the Institute. ★ ★ ★

Oklahoma Sections Hold Successful Meeting

The work of the Petroleum Branch took a step forward on April 27 with an all-day meeting at the Univ. of Oklahoma, sponsored jointly by Oklahoma City and Mid-Continent Local Sections. The meeting, for which 455 students and 55 industry representatives registered, was devoted to technical papers during the day, and a banquet in the evening.

John C. Calhoun, Jr., head of the petroleum engineering department at the university, was co-chairman of the morning session with N. Van Wingen, professor of petroleum engineering. Five technical papers were presented by persons other than students (see April JOURNAL).

J. P. Hammond and H. M. Cooley, outgoing and incoming chairmen of the Mid-Continent Section, presided during the afternoon program. A feature of this session was the presentation of student papers in a contest. James D. Murdock, Univ. of Oklahoma, presented *Methods of Recovering Oil from Athabaska Tar Sands*, the only undergraduate paper, for which he received a set of Petroleum *Transactions* as a prize.

Three papers were presented in the graduate student contest. Marsh S. Watson, Jr., Univ. of Oklahoma, presented *Interpretation of Field Data on the Basis of Relative Permeability*, which was co-authored by F. W. Gooch, also

John C. Calhoun, head of P. E. department in Oklahoma Univ., who presented *Mercury and Gas Absorption Techniques Applied to Capillary Pressure Methods.*

of the Univ. of Oklahoma. Competing with them were two graduate students from the Univ. of Tulsa. The first of these, W. D. Elliott, presented *Alignment Charts for Permeability Calculations*. The charts he presented were developed as part of his thesis.

The second Tulsa paper was presented by E. E. Barberii and was entitled, *Use of Perlite to Combat Loss of Circulation*. The judges selected this paper as the best of the graduate papers and awarded the cash prize of $25 to Barberii. He is a native of Venezuela who completed his undergraduate work at the Univ. of Oklahoma; returned to Venezuela and then came back to the United States for graduate work in the Univ. of Tulsa. He is now serving as associate editor of PETROLEO INTER-AMERICANO while attending the university.

The two hours from 4:30 until 6:30 were devoted to an inspection of exhibits in the Petroleum Engineering Building. Several scale models of drilling and recovery operations had been constructed by students and were set up for this meeting and the university engineering show which followed.

Over sixty people attended the banquet in the University Union Building in the evening. W. H. Carson, dean of engineering at the University, presented slides from pictures he had taken on a recent trip to Egypt. Henry Waszkowski, vice chairman of the Oklahoma City Section presided at the banquet, introducing Dean Carson and other guests.

Donald Powell, president of the Petroleum Engineers Club on the campus and Charles Olson, president of Tau Epsilon Pi, were responsible for the general arrangements of the meeting and received many compliments for the smooth manner in which it was executed. ★ ★ ★

Albert E. Sweeney, Interstate Oil Compact Commission, makes a point during his presentation of *Progress of Secondary Recovery in the Mid-Continent.*

A portion of the group attending the morning session of the meeting.

North Texas Section Activities

By Kenneth F. Anderson

The April meeting of the Section was held at the Melrose Hotel, Dallas, and about 85 members and guests were present to hear a talk by Alton B. Cook, petroleum engineer, Bureau of Mines, Bartlesville, Okla. The meeting was called to order by Chairman Don Harlan and a short discussion of local affairs of the Section ensued. The discussion resulted in the passage of a motion instructing Harlan to appoint a committee to investigate the feasibility of inaugurating special study groups in Dallas and Fort Worth.

The address, entitled "Special Considerations in Estimating Oil Recoveries from Reservoirs Producing High API Gravity Oils", proved very informative and considerable discussion followed. Cook presented data obtained from the North Lindsay field, McClain County, Okla., to demonstrate how the physical properties of the "highly-volatile-type reservoir oils" differed from the less-volatile type. After familiarizing the audience with some of the unusual physical properties of the reservoir oil from this field, data and sample calculations were presented to show the value of the condensate in the liberated gas that is produced with the oil. A summary of the talk follows:

Most of the solution gas in a "gas-expansion type reservoir" will be produced ultimately even though a large portion of the oil in place initially will not be produced. In some of the deeper reservoirs the solution gas that is liberated in the reservoir contains appreciable quantities of liquefiable hydrocarbons. When an oil well produces gas of this type condensate is collected in the stock-tanks along with the oil. Although most reservoir engineers are aware of this condition, little consideration has been given to calculating the volume of condensate recoverable from the production of solution gas liberated in the reservoir.

The volume of condensate recoverable from the production of solution gas liberated in the reservoir from most fields is negligible and has not warranted any special consideration. Numerous oil reservoirs, however, have been found in recent years at depths greater than 10,000 feet. In studying some of these deep-seated reservoirs for the purpose of calculating the ultimate volume of hydrocarbon liquid that will be collected in the stock-tank, it is important to consider the condensate that can be recovered along with the stock-tank oil. The volume of condensate recoverable from many reservoirs containing oil with a dissolved-gas content of more than 2,500 cu. ft. per barrel of residual oil may be greater than the recovered volume of stock-tank oil. (Stock-tank oil being defined as the liquid collected in the stock-tank from the liquid-phase fluid that enters the well-bore of a producing well.)

The calculated recovery of oil from reservoirs containing high API gravity oil usually is extremely low if no consideration is given to the volume of condensate that may be recovered with the high-gravity oil. These low calculated recoveries together with the high cost of drilling and completing the deep wells offer little encouragement for the development of reservoirs of this type. If proper consideration is given to the volume of condensate that may be recovered along with the high API gravity of oil, however, the total recovery of hydrocarbon liquid per acre-foot compares favorably with the recoveries of oil from the more usual solution-gas drive reservoirs.

In concluding his talk Cook described a method of conducting laboratory experiments on subsurface samples for the purpose of determining the composition of gas-phase fluid that would enter the well bore at various stages of depletion. Cook asserted that the volume of recoverable condensate can be calculated with a knowledge of the composition of the excess gas being produced with the oil and other data that usually are available.

May Meeting

John Campbell of Lane-Wells Co. will speak at the May 18 meeting in Fort Worth. ★ ★ ★

Alton B. Cook, with Bureau of Mines in Bartlesville, Okla., spoke on estimating recoveries in high gravity production at the April meeting in Dallas.

✦

Oklahoma City Section Briefs

By Harold Sells

The Section held the regular monthly meeting April 14 at the Biltmore Hotel. An interesting and informative lecture was presented by Gordon Jackson of the Eastman Oil Well Survey Co. on "Developments in Directional Drilling Techniques."

Personals

Under the direction of W. D. Owsley, Willard Hassebroek and C. E. Clason have been quite occupied with the inauguration of the new Hydrafrac process for rejuvenation of old sand wells and increased potential for those recently drilled. Hassebroek gave a talk on this service before the Denver Petroleum Engineers' Club and Owsley will be doing the same in other areas in the near future.

Albert R. Greer of Anderson-Prichard Oil Corp., Oklahoma City, is spending considerable time on the proposed Levelland Field (Texas) unitization and has recently attended committee meetings in Fort Worth and Midland.

Bill Hixon, Anderson-Prichard Oil Corp. district office in Oklahoma City, is making a detailed study of coring costs with diamond core barrels in the deep Garvin County Hunton and Bromide production. ★ ★ ★

Mid-Continent Section Activities

By Joe B. Alford

John T. Hayward, vice president of Barnsdall Research Corp., held the close attention of 80 members and guests of the Section during the April 19 meeting with his presentation of "A Unique Design for Offshore Drilling Equipment". The talk was an explanation of the construction and operation of a drilling barge-platform which was designed by Hayward and built for offshore drilling in the Gulf. A summary of barge design, construction and utilization follows:

The two methods most commonly used in offshore drilling are the drilling barge and a pile foundation. The barge has been successful only in shallow and very protected waters, and the cost of pile foundations is almost prohibitive. A third method of anchoring a converted LST to a pile foundation holding only the derrick still has difficulties because of the rolling of the ship.

The need still remains beyond these for more efficient offshore drilling equipment. One solution which would minimize some of the difficulties of existing methods was the modification of the shallow water barge to permit it to work in deeper, more exposed waters. This could be accomplished by building a superstructure on vertical steel columns welded to the top of the barge which could be submerged to bottom to form a foundation for the superstructure, from which drilling could be conducted, and on which the crew could live. The whole structure could be floated into place, submerged and used, then refloated and towed to another location.

Hayward applied this solution and one of the first problems encountered was how high to make the barge, and how high to make the drilling platform above it. The greatest water depth on the leases for which this barge was built is 20 feet. Since it was necessary to place the drilling platform on top of steel columns so that the waves could wash through them on location, these columns should reach above the wave crests. By the application of marine engineering, it was determined that the bottom of the superstructure should be 12 feet above mean water level, or a total of 32 feet above the floor of the Gulf. Since six tenths of a wave is above mean water level, with four tenths below, it was necessary for the top of the barge to be below the lowest part of the wave. Its necessary height was then determined to be 13 feet, which would place its top seven feet below the mean water level. The steel columns above it were then made 19 feet, placing the floor of the superstructure the required 32 feet above the floor of the Gulf.

The barge is of steel, and is 160 feet long by 54 feet wide. It is divided into compartments by water tight bulkheads, into which water is pumped to submerge the structure, and in which 3,000

John T. Hayward, designer of the drilling barge-platform. After obtaining an engineering education at Liverpool, England, he worked in shipyards at Belfast, and then went to work in the Rumania oil fields. He came to the U. S. in 1927, and became chief engineer for Barnsdall in 1931. He has been very active in oil industry research, and is a long standing member of AIME.

A view of the barge nearing completion in the Alexander Shipyards in New Orleans. The two men standing on the left side of the upper deck give an idea of its size. Floating at the left of the structure are the two pontoons used for stabilizing the structure in submerging-raising operations.

A view of the structure submerged on location. Here it resembles an ordinary pile foundation. In the background are parts of the superstructure of a war-surplus L.S.M. which was sunk to serve as a breakwater, and as a test to study bottom scouring action.

barrels of fresh water and fuels can be stored on location.

The drilling machinery and its power plant, together with the main electric generating plant, is located on the first platform above the deck of the barge. The barge is slotted to allow casing and drilling pipe to extend from the drilling platform straight through to the hole. Thirteen feet above the first platform is another deck which contains the derrick floor, the derrick, and the drawworks. This deck also contains the living quarters for the crew of 50 men. These quarters are completely air conditioned and have icebox and storage capacity to provide for three weeks' isolation. Rising eleven feet above the drilling platform is a recreational deck large enough for helicopter landings.

The installation complete with all drilling equipment weighs 1,800 tons and ordinarily draws five feet of water while being towed by a tug. It would appear that the vessel would be top heavy, but it works on the same principle as a rocking chair — the center of gravity is balanced above the base. The barge is stable until water reaches the level of the barge deck during sinking operations, at which time it becomes completely unbalanced. To prevent it from toppling during sinking and raising operations, a pontoon is placed on each side of the structure which remains on the top of the water and acts as a stabilizing outrigger until the barge sinks to the bottom. The pontoons are then sunk alongside, which increases the effective width of the whole structure, and because of a large fin on the bottom of each, helps to hold the structure rigidly in place.

Joseph Zaba of Tulsa spoke on "Modern Application of Gas Lift" at the April 25 Study Group Meeting.

The drilling barge-platform is now being used to drill a well in the Gulf which has progressed more than 9,000 feet. During this operation the barge has not sunk more than three inches into the bed of the Gulf; it has not moved an inch laterally and has deviated only one tenth of one degree from vertical.

The structure has the major advantages of costing only about two thirds as much of an ordinary pile structure, and of mobility for use in other locations. It will have paid for itself after the drilling of a single well, and Hayward estimates that from then on, it should save close to a half million dollars per location.

Study Group Meeting

A fine historical survey of gas lift operation from earliest times to the present day was presented at the April 25 meeting of the Production and Drilling Study Group. Joseph Zaba, mechanical engineering supervisor of Stanolind Oil & Gas Co. made the presentation in a talk on "Modern Application of Gas Lift". Approximately 100 members and guests attended the meeting.

NEW SECTION OFFICERS TO BE INSTALLED MAY 17

STANDING, L. to R.: P. P. Manion, Jr., proration supervisor of Stanolind Oil & Gas Co., past chairman and ex-officio member of executive committee; J. H. Beesley, division sales manager of Baroid Sales Division, secretary-treasurer; and J. P. Hammond, asst. to vice pres. of Amerada Pet. Corp., outgoing chairman and ex-officio member of executive committee.

SITTING, L. to R.. R. H. Smith, asst. to chief engineer, Stanolind Oil & Gas Co., first vice chairman; H. M. Cooley, asst. metallurgical engineer, Bethlehem Steel Co., chairman; and J. N. McGirl, dist. mgr. of exploration, Tide Water Associated Oil Co., second vice chairman.

May Meeting

A joint meeting between the section and the Reservoir Study Group will be held on May 17 at Lorton Hall. A. F. van Everdingen of Shell Oil Co., Houston, will present *Application of the La Place Transformation to Flow Problems in Reservoirs.* This will be the last meeting before the summer recess.

Personals

ROBERT G. HAMILTON, area manager of Schlumberger Well Surveying Corp. for Oklahoma, Kansas, North and West Texas and New Mexico, will be transferred to Houston in June, where he will be manager of the company's Sales Department in that area. He joined Schlumberger in 1935 in the Gulf Coast area, went to Oklahoma City in 1937, then to Tulsa in 1939, where he remained until the present. He has been very active in the Mid-Continent Section activities, having held several offices, and served as chairman in 1943. ★ ★ ★

Members of the panel which discussed oil well completion at the April meeting. Rear, left to right: C. A. Davis, Richfield Oil Corp., J. A. Klotz, Calif. Research Corp., M. E. Loy, Schlumberger Corp., and R. L. Parsons, Calif. Research Corp. Front, left to right: W. Robinson, Texas Co., John Fraser, Union Oil Co. and John Hills, General Pet. Corp.

Junior Group Activities
Pacific Petroleum Chapter

By Al Marshall

One of the best meetings of the year was held on April 14 at the Rio Hondo Country Club. A panel on oil well completion problems was the center of interest for the meeting, which 162 members and guests attended.

Harold J. Clark of Los Angeles, who is chairman of the Southern California Local Section and a member of the Council of Pacific Petroleum Chapter.

Charles McClure, group chairman, opened the meeting by welcoming the unusually large attendance and introducing Harold Nissen, the new membership chairman. The meeting was then turned over to R. L. Parsons who introduced the panel of speakers on oil well completion and served as moderator for the discussion. The members of the panel as introduced by Parsons were: W. Robinson, director of research for the producing department laboratory of the Pacific Coast division of the Texas Co. and chiefly interested in the application of chemistry to drilling and producing problems; John Hills, an engineer with General Petroleum Corp. and graduate of the Univ. of Southern California, and author of the API paper, *Design of Casing Problems;* C. A. Davis, the home office production engineer for Richfield Oil Corp. who has done considerable work on deep well pumping problems and reservoir engineering in the California oil fields; John Fraser, division engineer with Union Oil Co. who has had wide experience in many phases of well completion and petroleum engineering during the last fifteen years; J. A. Klotz, a research engineer with the California Research Corp. and a graduate of Northwestern Univ. and the Univ. of Michigan in chemical engineering; and M. E. Loy, assistant manager of the Pacific Coast area of the Schlumberger Corp., who has had wide experience in logging California wells.

The discussion was opened by a member of the audience asking the simple but elusive question, "I drilled a dry hole in the middle of a producing oil field. Why?" In trying to solve this gentleman's problem the panel discussed the relative merits of displacing drilling mud with oil or water. It was unanimously agreed by the members of the panel that oil is the most preferable displacing fluid in the majority of cases; however, they felt that it is possible to have a filter cake of such character that water would be a preferable displacing fluid, particularly where wall scratchers were not used. W. Robinson offered the suggestion that possibly too much emphasis is being placed on the water loss of drilling fluids and that not enough emphasis is being placed on the removal of the filter cake during the well completion.

One member of the audience asked the panel what experiences they had had with the use of the Hydrafrac process to increase permeability in California sands. The panel answered that this process had not been used in California.

The original question of "What is wrong with my oil well" brought continual suggestions from both the audience and the panel and several lively disputes resulted while the discussion of this subject was going on. ★ ★ ★

Al Marshall, left, secretary, and Norman B. Clark, right, program chairman for the Junior Group during 1949.

Pacific Petroleum Chapter Activities

By Frank Parker

The Petroleum Technology Forum met April 21 to hear Wayne Glenn of the Continental Oil Co. discuss *Performance History of the First Grubb Pool of San Miguelito Field.* Glenn, who is a native of Fort Worth, Texas, and graduate of the Univ. of Oklahoma, has been with Continental seven years in Texas, New Mexico, Oklahoma and California.

The San Miguelito Field, a steeply folded and faulted anticline, has two defined pools, but discussion was limited to the First Grubb, the discovery pool and the one higher in the section. The oil occurs in a steeply folded and faulted anticline. The field was discovered in 1931 by Continental who is the only operator and at present has drilled some 50 producing wells with no dry holes. About 1200 feet of section made up of five sand bodies with intervening shales is treated as a single pool. To the end of 1948 about 15,000,000 bbls. of oil and 4,000,000 mcf. of gas have been produced with a pressure decline from 3000 to 1700 psi. The spacing is rather uniform at 6½ acres accomplished by direction drilling because of extremely rugged topography.

Wayne Glenn of Continental Oil Co. spoke on the First Grubb Pool of San Miguelto Field at the April meeting of the Technology Forum.

Permeability as determined from 622 samples decreased generally downward from about 325 md. to 36 md., the average being 86 md. Porosity ranges from 21% above to 15% lower down. Faulting is present but is not effective as a barrier, perhaps in part because of completions of wells through the fault plane. Water influx is localized both vertically and horizontally and so far has reached only two marginal wells. Effect of gravity drainage is not susceptible to calculation as at times the drainage pattern has caused flow of oil up structure.

Low pressure gas injection has been practiced since 1940 but is not a pressure maintenance project, the threefold purpose of the injection being to sweep through selective permeable oil sands which have been resaturated by oil from less permeable sands, to conserve gas by adjusting output to demand, and to prolong the flowing life of the wells. The selective sweep will be accomplished by cementing the blank intervals opposite the shale bodies setting plugs and packers to sweep sub-zones of the pool in turn and repeating the process as the sub-zones become resaturated. It is believed that high pressure injection would largely prevent resaturation and that recovery will be greater using low pressure. The talk was supplemented by a wealth of engineering data, interpretive maps, charts, and sections.

Continued on Next Page

Charles W. Gates, chairman of the Petroleum Technology Forum for 1949.

A portion of the group at the April meeting of the Technology Forum.

Mississippi Sub Section Activities

By Sam J. Poythress, Jr.

Sam. J. Poythress, Jr., JOURNAL Secretary for the Mississippi Sub Section. A native of Shreveport, La., and a graduate of LSU in P.E.; served two years with 3rd Inf. Div. in North Africa. After the war worked with Core Labs., and since 1947 with Gulf Ref. Co. in Laurel, Miss.

R. E. France, district operating supt. for The California Co. in Natchez, is chairman of the Sub Section for 1949.

A dinner meeting of the Sub Section was held Thursday, March 29 at Laurel, Mississippi. Refreshments and a buffet style dinner were served in the Rumpus Room of the Gulf Building, and the business meeting was held later in the same building.

The chairman of the Sub Section, R. E. Franch of California Co., Natchez, presided for the first time since his election, as he had been unable to attend the January 28 meeting in Jackson. France introduced E. N. Dunlap, California Research Corp., New Orleans, chairman of the Delta Section, who had attended the San Francisco Annual Meeting. He gave the members an interesting account of the activities there. The business sessions were discussed fully with emphasis on the financial status of the Institute and of the Petroleum Branch, and the referendum concerning the membership dues inincrease.

W. W. Ramseur of Gulf Ref. Co. in Laurel introduced the featured speaker of the meeting, Walter F. Rogers, chief chemist for the Gulf companies in the Houston laboratories. He is author of the book *Composition and Properties of Oil Well Drilling Fluids*, and an authority on corrosion and other phases of oil field chemistry. He was accompanied by H. E. Waldrip, also with Gulf in Houston.

The title of the paper Rogers presented was *Corrosion in Condensate Wells*. The speaker made his subject understandable and interesting to all his listeners and had an eager audience throughout his presentation. Oil field corrosion has become a serious problem throughout Mississippi and particularly in gas-condensate wells. The fact that many of the case histories studied were from Mississippi fields served to increase interest in the paper.

Eighty-two persons attended the meeting and plans were announced to hold the next meeting in Brookhaven in mid-May. Frank A. Goerner, California Co., Brookhaven, was appointed program chairman for this meeting. ★ ★ ★

Albert W. Gunther, division field engineer for The California Co. in Natchez, is sec.-treas. of the Sub Section for 1949.

PACIFIC CHAPTER

Continued from Page 13

Personals

JOHN DE HETRE, a former active member of the Chapter, has been promoted to manager of tubular sales for the oil industry for Youngstown Sheet and Tube Co.

HOWARD SWEET has been made Pacific coast manager of Kobe. He has been with that organization since 1945 in the coast area.

Pacific Petroleum Chapter Mailing List

The mailing list of the Chapter is to be extended to include all Petroleum Branch members on the Pacific coast and at the same time revised and corrected. All Petroleum Members and others interested who are not now on the mailing list or have made a change of address are requested to furnish their name and address to Frank S. Parker, Secretary-Treasurer, Box 5840, Metropolitan Station, Los Angeles 55, Calif. ★ ★ ★

Kansas Section Activities

By Carl Lund

W. A. Heath of Earlougher Engineering Co., speaker for the April meeting.

W. A. Heath of Earlougher Engineering Co. in Tulsa was the principal speaker at the Section meeting on April 8. He discussed how old wells have been and can be used in a secondary recovery program.

Heath said that the prime advantage of using old wells is a large saving in development costs. Disadvantages consists of irregular spacing, poor mechanical condition of the well bore, exposed gas, or thief formations which may be difficult to isolate because of having been shot with nitroglycerin.

Deposition of paraffin and other residues in the well bore is troublesome in certain areas, particularly the Eastern district, and if not removed prior to conversion of an old well to an input well, it may greatly reduce the efficiency of the driving medium. In the Mid-Continent district little difficulty is encountered in deposition of residues, and no special precaution other than a mechanical clean-out is performed in conversion of a well to input. In some instances precipitation of calcium, barium, and strontium salts on the sand face has occurred and special treatment is required.

Heath concluded his presentation by discussing the reasons for intensive secondary recovery in some areas.

Field Trip

Paul Witherspoon reported that the field trip through the Greenwood County water flood properties would be held on May 19 at 2:00 p.m. This tour will be in conjunction with the Kansas-Oklahoma Water Flood Operators Group. The students of petroleum engineering at Kansas Univ. are making this their official field trip of the year.

The following properties will be visited on this tour, with the water flood engineer of each company explaining his operations; Phillips Pet. Co., Burkett Unit; Magnolia Pet. Co., Seeley Unit; and Cities Service Oil Co., Cloupton Unit.

After the field trip, Ward A. McGinnis, independent operator of Eureka, Kansas, will be host to the Section with a barbecue dinner at his ranch. ★ ★ ★

Three Fellowships Announced for P. E. School of Oklahoma University

Three new fellowships have been established for the Oklahoma Univ. School of Petroleum Engineering under the names of Shell, Humble and Stanolind. All three are for a one-year appointment beginning September 1, 1949, and are only open to candidates for the masters degree in petroleum engineering.

The Shell Fellowship stipend amounts to $1,200 per year, plus an additional $300.00 per year for the purchase of research equipment. It was established by the Shell Union Oil Corp. and its associated companies.

The Humble Fellowship, which was established by the Humble Oil and Gas Co., provides a stipend of $1,250.

The Stanolind Oil & Gas Co. established the Stanolind Fellowship, which provides a stipend of $1,250 per academic year. It specifies that graduate research study will be carried on in the field of displacement of oil from reservoir material.

Applications for all three fellowships are invited from men with bachelor's degree in petroleum engineering or related fields from an accredited school. They should be sent to Dr. John C. Calhoun, Department of Petroleum Engineering, Faculty Exchange, Univ. of Oklahoma. Full particulars should be given in the first letter of transmittal and should include: name, age, marital status, complete college record with transcripts, three letters of recommendation, status under G. I. Bill, and other pertinent details. All applications should be received not later than June 10, 1949. ★ ★ ★

Gulf Coast Section Activities

By Frank Briggs

At the monthly meeting of the Section on April 19 approximately 150 members dined in sumptuous fashion at the Houston Y.M.C.A., and led by Chairman Owen Thornton, enthusiastically welcomed William (Bill) Murray, who delivered the principal address.

Laying aside his political mantle, Murray, who, as chairman of the Texas Railroad Commission, represents one of the strongest regulatory bodies in the entire country, preferred to be considered as another petroleum engineer discussing mutual problems. The subject of his talk was entitled, "Progress Report on Conservation".

In his preliminary remarks, Murray pointed out that there is a world-wide consciousness recognizing the tremendous importance of the conservation of natural resources. As an example of this, he pointed out that the United Nations has recently set up a proposed conference on conservation to be held in the autumn of this year. Sounding a note of alarm, he said that the American people have and are wasting our resources at a more rapid rate than ever before. He attributed this waste to lack of economic incentives, lack of cooperation between industry and the public, a complete misunderstanding by the public of the problems presented, and the employment of poor or unsound engineering principles by industry. This public consciousness is at last awakening from the lethal apathy that has been predominant in the past. In reporting the progress obtained through the cooperation of the petroleum industry, the Railroad Commission, and the general public, Murray used as an example the problem of flare gas. Of seventeen "show cause" cases involving a like number of producing fields, he reported that wherever it was good practice to return flare gas or process it, plants have been set up and wastage thereby eliminated. Such fields as Fullerton, Foster, North Cowden, Goldsmith, Seminole, Slaughter, Wasson, Conroe, and two or three others now have compressor plants of capacities sufficient to receive all flare gas formerly wasted in the atmosphere. Of the seventeen test cases, only one has been tried in court (with a decision handed down sustaining the authority of the Railroad Commission to close in this field) and only one more court action will probably be filed.

Pointing out that this utilization of flare gas has already cost the industry approximately one-quarter billion dollars, and that returns thereto are long-range and represent a conservation rather than profit incentive, Murray listed this as an example of the cooperation received from the oil industry.

He voiced a prediction that the present trend in conservation will make it a public duty for the industry to spend money for plants and equipment involving projects where public interest rather than profits are evidenced. The industry was also admonished to maintain the lead in the conservation program. The legislature and the courts, at one time lagging behind the progress of the industry, are now most progressive minded and have taken up the slack that formerly existed in thinking of conservation.

Engineers Symposium

As a member of the Engineers Council of Houston, the Section participated in the second annual symposium on April 2 sponsored by local branches of 17 professional organizations. Theme of the meeting, which was highly successful, was "Conservation of Our Natural Resources". Paul Weaver, chief geophysicist of Gulf Oil Corp., Houston, and an AIME member of long standing, presented one of the four papers on this theme entitled "Conservation of Water."

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Employment Notices

The JOURNAL will post notices of men and jobs available. Companies and AIME members are invited to use this space, for which there is no charge. Except as noted below, address replies to: Code (appropriate number) JOURNAL OF PETROLEUM TECHNOLOGY, 601 Continental Bldg., Dallas 1. Show return address on envelope. These replies will be forwarded unopened, and no fees are involved.

Replies to items coded M-430 and Y-1814 should be addressed to Engineering Societies Personnel Service, 8 West 40th St., New York 18, N. Y., on whose behalf they are published here. The ESPS collects a fee from applicants actually placed.

PERSONNEL

♦ Geologist, M.S. Degree in Geology. Eleven years' experience; three years' teaching, three years' hardrock geology and five years' petroleum geology in tropics. Speaks fluent Spanish. Age 36, married, one child. Available for foreign service, preferably Colombia. Code M-430.

♦ Petroleum Engineer—B.E.M. in P. E. Several years' experience in U. S. and three years' experience in Colombia and Venezuela, S. A., in drilling, well completions, and production engineering. Age 34, married. Prefer good position with opportunities in foreign operations. Code 103.

POSITIONS

♦ Petroleum Engineer — located in the mid-continent states, with excellent company. Experience as petroleum engineer necessary requirement. Starting salary commensurate with experience and qualifications with $400 a month minimum. Code 507.

♦ Chemical Engineer — (a) Chemical engineer or chemist with oil refining experience for process development of asphalt products. Salary, $3000-$4000 a year. (b) Chemical engineer with oil refining experience to run pilot plant tests on asphalts. Salary, $4000-$5000 a year. Located in Maryland. Code Y-1814.

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East Texas Section Activities

By Roy F. Beery

The territory of the Section includes parts of Arkansas and Louisiana as well as East Texas and for that reason, at least two of the monthly meetings in each year are held in Shreveport with the remaining meetings held at Kilgore. The April meeting, held at Monsour's Restaurant on April 12, was the first to be held this year at Shreveport and was attended by approximately 30 members and 40 visitors. The entire membership of the Shreveport Geological Society was invited and a large portion of the visitors was from this group.

Vice Chairman W. W. Leonard presided at a brief business session and announced that the next meeting would be held at Kilgore on May 10. Featured speaker for the May meeting was J. C. Slonneger, assistant chief engineer for Continental Supply Co., Dallas. Slonneger spoke on "Desirable Characteristics of Oil Feld Pumping Engines."

Roland Thies, program chairman, introduced the principal speaker of the evening, P. S. Erwin, petroleum engineer with Frank N. Speller, Jr., consultant of Tyler, Texas. Before turning the audience over to Erwin, Thies proudly called the visitors' attention to the projector to be used for illustrating the paper. After borrowing projectors for several years, the Section recently purchased a Bausch & Lomb Opaque Balopticon projector, which can be used to project opaque charts, either colored or black and white, as well as several different sizes of slides.

W. R. Mays of Kilgore has joined the staff of Kilgore Junior College to instruct in the drilling practices course. He was previously sales engineer with Halliburton in that area.

Erwin, a native of Louisiana and a 1938 graduate of Louisiana State University, was with the Haynesville Operators Committee for four years before joining Speller's staff. His paper, *Gas Injection and Water Flooding of the Pettit in the Haynesville Field, Claiborne Parish, Louisiana,* represented a reservoir analysis of the stratigraphic and structural traps present in the Upper and Lower Pettit formations of this field.

The Haynesville field was discovered in 1941 and now contains 189 wells. All but two of the wells were included in a unit in 1944, and in 1945 compressors were installed to inject approximately 16 million cubic feet of gas daily. The injection of gas successfully retarded the rate of decline in reservoir pressure but the produced gas-oil ratio continued to exceed efficient limits. In an effort to improve reservoir conditions, a water injection program was adopted in 1946. The combination gas and water injection program increased oil production and reduced the gas production. Erwin presented numerous graphs and plats as well as tabulated data to illustrate the history of the field. In addition, detailed data used to estimate the oil and gas reserves were submitted. Based on the data available, Erwin estimated the Upper and Lower Pettit formations would ultimately produce a total of approximately 41 million barrels of oil. The field has now produced 21½ million barrels and the future production of 22½ million barrels is based on continued operation of the gas and water injection programs.

Personals

B. F. Patterson, Jr., petroleum engineer with the Texas Co., has been transferred from Gladewater, Texas, to Shreveport, Louisiana. The transfer carried with it a promotion to district engineer.

Earnest J. Mills, project superintendent with Barnsdall Oil Co., has recently been transferred to Benton, Louisiana, and is attending the East Texas Section meetings.

W. R. Mays, formerly sales and service engineer with Halliburton Oil Well Cementing Co. at Kilgore, has joined the staff of the Kilgore Junior College. Randolph Watson, Director of Vocational Education at the college, recently announced that Mays would be an instructor in the Drilling Practices Course. The college has a rotary rig and students obtain practical drilling experience in the field. ★ ★ ★

P. S. Erwin, speaker for the April meeting. He presented *Gas Injection and Water Flooding of the Pettit in the Haynesville Field, Claiborne Parish, Louisiana.*

Delta Section Activities

By Fred E. Simmons, Jr.

More than one hundred members of Delta Section heard C. Leslie Rice, Jr., assistant vice president, Empire Trust Co., New York, in his address Tuesday evening, April 12, on *Private Financing of Oil Producing Properties*, at the New Orleans Petroleum Club. This paper was presented in full in the January JOURNAL.

The speaker showed a thorough and detailed knowledge of all phases of oil banking and won much applause with his humorous treatment of some of the problems encountered in his professional contact with the oil industry.

The speaker stated in part, "In viewing oil loan collateral the banker invariably considers first and foremost, 'Can we get our money back from the production or liquidation of this collateral?' Bankers as lenders cannot afford nor are they permitted to put their principal 'at speculative risk'. Commercial bankers lend capital which they themselves borrowed from depositors. Bankers must handle these entrusted funds in the manner which in their opinion best assures repayment."

Rice brought out the point that banks, in making loans, look for the "practical oil man" who knows the oil business, who has a stake in the success of his property, and who can be counted on to consistently give his best efforts to the operation of the property. Banks are not very interested in making loans which they cannot see being repaid within a maximum of ten years.

C. Leslie Rice, Jr., with Empire Trust Co. of New York, spoke on oil property financing at the April meeting in New Orleans.

High tribute was paid to the engineers and geologists on whose evaluation reports the banks depend for guidance in making oil loans. Without facts gathered and compiled by these specialists, nothing would be accomplished, but with their information at hand, properly assembled and interpreted, the problems of sound oil financing can be clearly met and dealt with in the best interest and to the mutual benefit of all concerned.

E. N. Dunlap, Section chairman, presided at the meeting with Vice Chairman H. M. Krause and Secretary Fred Simmons, who introduced the speaker. It was announced that Barney Francis of the Texas Co. had been elected treasurer of the section.

Benj. C. Craft of the LSU petroleum engineering department was present and gave an outline of some of the student papers which are being prepared for the student paper competition in May. E. N. Van Duzee of Shell Oil Co., chairman of the activities committee, also spoke briefly.

At the Tuesday luncheon meeting of the Delta Section Executive Committee, which was attended by Rice and W. H. Strang, executive secretary of the Petroleum Branch, preliminary plans were laid for a 1950 annual meeting of the Branch which may be held in New Orleans.

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Permian Basin Section Activities

By Tom W. Flewharty

Over 150 members and visitors attended the monthly meeting of the Section held April 4 at the Roski Club in Odessa. It was the largest attendance in the Section's history.

Chairman Tom Frick opened the meeting with a short business session, and announced that at the next meeting a vote will be taken on the question of changing the by-laws of the Section to enable the officers to be elected in December of each year rather than in January. He said that this step would eliminate some of the confusion that often has resulted from the delay in the new officers taking charge.

Frick also announced that two members have been appointed to the program committee and one to the membership committee of the Section. The program committee now consists of Chairman W. N. Little, Tide Water Associated Oil Co. in Midland; Ed Shakely, Shell Oil Co. in Midland, and F. L. Converse, Stanolind Oil & Gas Co. in Midland.

Those on the membership committee now are Chairman Joe Chastain, Bethlehem Supply Co. in Midland, and James C. Wright, Garrett Oil Tools in Odessa. A third member will be appointed to this committee at a later date, Frick said.

R. H. McLemore, vice president of Welex Jet Services, Inc. in Fort Worth, was the speaker for the meeting with his paper on *The Jet Process of Perforating Oil Well Casing*. The paper was reviewed in the East Texas Section Activities in the February JOURNAL.

After McLemore had completed his presentation a discussion of the topic was lead by C. E. Shilcutt, Lane-Wells Co. in Odessa, and John F. Younger, The Younger Co. in Midland. ★ ★ ★

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Film Reviews

The following film reviews are presented as possible material for use in local section meetings. Write directly to the address given in the review.

10,000 FEET DEEP

16mm sound, black and white, 20 minutes, 1948

Dramatically shows how modern science has provided methods for locating the exact depth of oil deposits thousands of feet underground. Depicts modern methods of drilling for oil. Begins with brief description of oil's prehistoric origin. Relates picturesque episodes in oil exploration, showing how modern science has replaced superstitution. Demonstrates how geologists charge a region likely to bear oil, including various tests made to determine location and depth of underground arch or anticline of rock.

Shell Oil Company, Inc., 50 West 50th Street, New York 20, N. Y.

Shell Oil Company, Inc., 100 Bush Street, San Francisco 6, Calif. Free on loan from both New York and Pacific Coast Offices.

THE UNDERSEA SEARCH FOR OIL

16mm sound, color, 20 minutes, 1948

Depicts pioneer drilling operations off-shore in the Gulf of Mexico. Shows erection of special drilling platform and subsequent steps in rigging and spudding in of first well.

Magnolia Pet. Corp., Magnolia Bldg., P. O. Box 900, Dallas, Texas, Att.: John Terrell. Free on loan.

PETROLEUM

16mm sound, black and white, 10 minutes, 1947

Animation and live-action photographs show the importance of petroleum to world technology, and suggest some of the critical political and economic problems related to its production and distribution. Essential steps in exploration, drilling and refining procedures are outlined. Maps show location and relative importance of oil producing areas of the world. Special emphasis given to petroleum resources of the U. S. Dramatic position which petroleum occupies in world commerce and international affairs is clearly set forth.

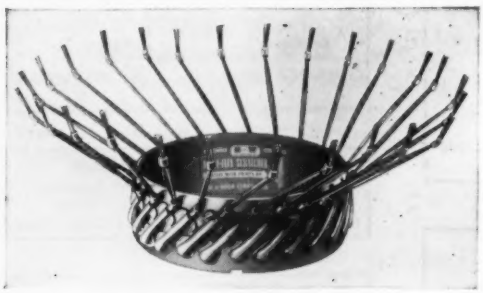
Encyclopedia Britannica Films, 1150 Wilmette Avenue, Wilmette, Illinois. Rental. Sale price $45.

BIRTH OF AN OIL FIELD

16mm sound, color, 31 minutes, 1948

Second film in the series "This Is Oil", shows how an oil well is drilled and how crude oil is brought up from the ground and started on its way to the refinery. After picturing the erection of the derrick, the film describes the operation of the ponderous equipment by drilling crews, follows the drill-bit as it makes its way through various geological strata, and tells how chemically treated mud is an invaluable aid to drillers. The film then depicts the natural forces that make oil flow, and shows how artificial methods lift oil from the ground when natural pressures decline.

Shell Oil Company, Inc., 100 Bush Street, San Francisco 6, Calif.; free on loan from both New York and Pacific Coast Offices. ★ ★ ★



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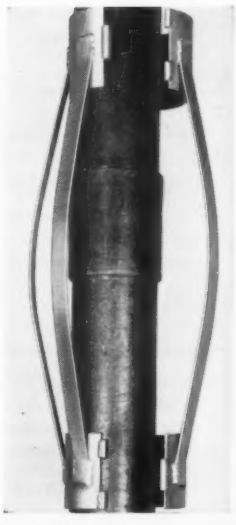

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To Members of the AIME:

For three years your Institute has been operating at a deficit, caused primarily by the increased cost of printing. This deficit has been largely met by borrowing from certain of the Funds which have been established for specific purposes by their contributors. Including an estimated $50,000 loss in operations for 1949, these borrowings will have reached the staggering sum of $150,000 by the end of the current year. Obviously, the Institute cannot continue to function on this basis.

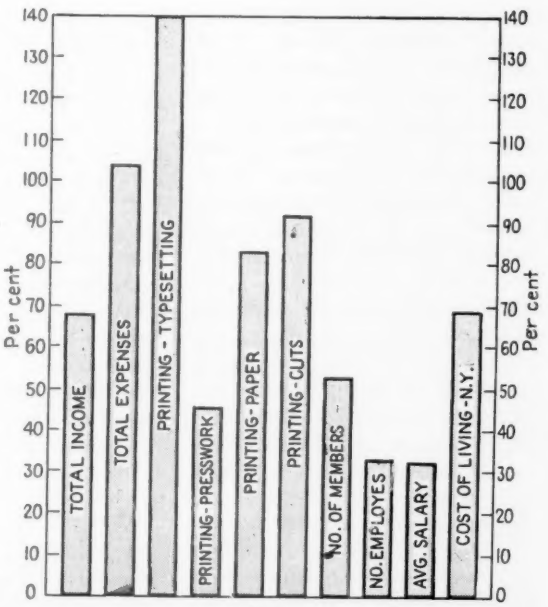
The Institute's main sources of revenue are advertising and membership fees. Every effort is being made to increase advertising revenue and to this end a new publication policy has been adopted whereby we put out three magazines, each in specialized fields, instead of *Mining and Metallurgy* and the four *Technologys* as heretofore. When these magazines become well established we have every reason to expect that the advertising revenue will be considerably greater than it was, but it may take three years to reach this goal. As to membership dues, a comparison with those of the other Founder Engineering Societies shows that ours are the lowest.

Taking due account of these two factors, the Section delegates at the San Francisco meeting recommended to the Board of Directors that a ballot be submitted to the membership to provide for an increase in dues, for a three-year period commencing in 1950, of $5 for Members and Associate Members and $2 for Junior Members. The Board of Directors unanimously approved the recommendation of the Section delegates.

It is estimated that this increase in dues will amount to approximately $50,000 per annum, which would permit a balanced budget in 1950 based on 1949 estimated income and expenditures. At the end of the three-year period another referendum vote will be taken, at which time dues for the succeeding years will be determined, based upon the conditions then prevailing.

A ballot will be sent to each voting member of the Institute in the latter part of May and you are urged to vote affirmatively in accordance with the recommendation of the Section delegates and the Board of Directors.

L. E. YOUNG
President



Percentage increases of various items 1948 over 1939.

Big Turnout of Directors Studies Vital Institute Problems at Six-Hour March Board Meeting

Nineteen Directors—a majority of the Board—spent six hours with their sleeves rolled up discussing important Institute problems at the meeting in New York on March 16. One out-of-town Director wrote back after returning home that he would come to the next meeting prepared with a knapsack and sleeping bag. A new procedure was tried for the first time: the usual monthly luncheon meeting of the Executive and Finance Committees was dispensed with, and instead the entire Board gathered at the Engineers' Club for a 12:30 luncheon and informal session without guests. Then two hours later, the regular open meeting got under way, and lasted until ten minutes to seven. President Young presided, the other Directors present being Messrs. Alford, Daveler, Elkins, Head, King, Kinzel, Kraft, McLaughlin, Meyerhoff, Pehrson, Peirce, Phillips, Price, Rhines, Schumacher, Suman, Swift, and Fletcher. T. B. Counselman acted as alternate for S. J. Swainson. In addition, absentee comment on various items on the agenda was received from Oliver Bowles, H. N. Eavenson, Louis D. Gordon, and T. S. Washburn.

more advertising income

One of the vital matters discussed at length was the problem of increasing the income of the Institute through advertising in the new journals. Considerable opposition had developed to the suggestion that an over-all advertising manager, or publication manager, be secured, at least for the present. The Petroleum Branch, especially, wished to contiuue its present efforts to build up advertising with only its staff at the Dallas office. The problem was believed most critical with the *Journal of Metals*, and authority was voted to secure an advertising solicitor immediately for this magazine. Mr. Schumacher, chairman of a small committee that had been appointed to consult with advertising men, reported their views, and Theodore Marvin gave the group the benefit of his experience as both a "space" salesman and buyer. Wheeler Spackman reported increased billings in the first quarter for *Mining Engineering* compared with *Mining and Metallurgy* last year, in spite of the loss of some advertising to the *Journal of Metals*. Advertising income for the three new journals should, it is believed, exceed that of last year by at least $30,000. "Publishers' representatives" may be used to augment regular staff coverage.

proposed dues increase

Another matter of great importance was consideration of the action of the Section Delegates at the San Francisco meeting, recommending to the Board an increase in the dues of Members and Associate Members of $5, and of Junior Members of $2, for three years ending with 1952. The Committee on Ways and Means had been asked to study this proposal, and Mr. Kraft, chairman, presented a summary of the financial condition of the Institute. If advertising income could be raised to $85,000 this year, and certain economies made, the deficit might be reduced to about half what it was in 1948, or some $42,000. This would bring the accumulated deficit for recent years up to about $150,000. The proposed increase in dues should increase yearly income by $55,000 to $60,000 for the three years, which would slightly more than offset the borrowings that have been necessary to meet the deficit. In 1952 a referendum would be taken as to whether or not the increased dues should be continued in the light of conditions at that time. The Board voted to accept the recommendation, and to conduct the required referendum of the membership. If the vote favored the increase, the necessary change in the bylaws would be voted on at the June meeting of the Board.

Other proposed changes in the bylaws to be acted upon by the Board at its June meeting will restore Jan. 1 as the date when dues become payable, with three months of grace allowed before members cease to be in good standing and the journals are cut off; and will dispense with the grade of Junior Foreign Affiliate at the end of 1949. The date when dues become payable had been changed to Oct. 1, but to increase the efficiency of work in the Institute's accounting department it is felt that mailing of the bills should be staggered through the months of September, October, November, and December.

Annual Meeting in St. Louis?

Shortly before the Board met, an invitation had been received from the St. Louis Section, the St. Louis Chamber of Commerce, and the St. Louis Convention and Publicity Bureau, inviting consideration of St. Louis as the scene of the Annual Meeting in 1951. Time had not permitted mature consideration of the proposal, so acceptance was postponed until the April meeting of the Board.

Mr. Schumacher, chairman of the Committee on Local Section Appropriations, reported his difficulties in making the available money—which the Board had set at approximately the same figure as last year, $9000—meet the needs of the Local Sections. Many had offered excellent arguments for increased allocations, up to $600 each though the Bylaws set a limit of $400. The Board was sympathetic to the needs of the Local Sections, many of which were believed to be doing an exceptionally fine job, but, with the depleted finances of the Institute, could not see its way to raise the total appropriation. The Local Section reports were studied carefully, and the fairest division possible was made. However, to alleviate the situation to some extent for the Local Sections, each was voted 10% of the initiation fees paid by all new members in its territory. This will be effective with the April elections. Thus a Local Section will receive an extra $100 if fifty new Members or Associate Members are elected from its area in the course of a year.

cost-cutting ideas

Mr. Elkins reported that the Petroleum Branch was planning issuance of a Directory of its members in the early summer, to be financed from its own funds. No complete Institute Directory is to be published until 1950. He also offered various recommendations designed for increased economies and efficiencies in the conduct of Institute affairs, suggesting that committees be appointed to study these matters. He was assured, however, that the Board and staff had already given close study to some of the suggestions and were keenly alive to the need for cutting costs in every way possible consistent with maintaining the essential services of the Institute. Particularly, Mr. Elkins thought that all meetings should be self-supporting in justice to those who could not attend them. In this the Board fully concurred, and voted that registration fees and other charges at all Annual, Regional, and Divisional meetings be set at such figures that they would be self-supporting to the fullest extent possible.

Chairmen of the Institute's standing committees for 1949-50 were announced and the complete committee personnel, with Local Section and Student Society officers, will be published in the June issues of the three journals. Certain inactive committees will be discontinued.

The Committee on Nominations for Institute Officers reported some difficulties in interpreting the rules and selecting candidates that properly represented the professional and geographical divisions of the membership. President Young was therefore authorized to appoint a committee of three to revise and clarify the "Instructions and Advice" to members of this Committee.

segregating Transactions material

Some members had reported a preference that the Transactions volumes be published by Divisional subjects, as in the past, rather than combining all the technical publications of a Branch, as is the plan for the future. Mr. Price, especially, reported the wish of the Coal Division that its papers be segregated, both in *Mining Engineering* and in a Transactions volume. This could be done, it was reported, either by holding the type for a year or more, or by separate offset printing of the desired papers, but either would be more costly than the present practice. The Board felt that the matter should be reconsidered before the end of the year, with relative costs considered.

Suggested plans for special committees of the Directors to consult frequently with the editorial boards of the three Branch journals were discussed, but it was felt that if Directors keep in close touch with the officials of the Branch they represent, and the Secretary keeps himself apprised of the wishes of members at the Local Section level, no further organization should be necessary. A continuous sampling of reader opinion on *Mining Engineering* is under way for the guidance of the editorial and advertising staffs.

delegates and representatives

Among the routine matters disposed of were the following: W. H. Carson was appointed an official delegate to the World Engineering Congress in Cairo. E. H. Robie was appointed as a director of the Engineering Societies Personnel Service. A. Rodger Denison was appointed an AIME director of the American Geological Institute for the term ending November, 1949, and Joseph L. Gillson for the term ending November, 1950. Approval was given the proposal to invite G. Borelius, a professor at the Techniska Högskolan, Stockholm, as Institute of Metals Division Lecturer for 1951. Francis B. Foley was appointed to represent the AIME on the Engineers Joint Council Committee on Collective Bargaining by Engineers in Professional Work.

Howard A. Herder was named to represent the AIME on the Washington Award Commission for a two-year term, to May, 1951. Gail F. Moulton was appointed to succeed Ralph M. Roosevelt as an AIME representative on United Engineering Trustees for a four-year term expiring in October, 1953. R. M. Brick and Francis B. Foley, with A. W. Grosvenor as alternate, were appointed official delegates to the meeting of the American Academy of Political and Social Science at Philadelphia, April 8-9. Approval was given to the continuance of the Alloys of Iron Research as an AIME-sponsored Engineering Foundation project for 1950 and 1951. A price of $3 to members and $5 to nonmembers was set for the translation, in one volume, of the old German books, "Probierbuchlein" and "Bergbuchlein," soon to be published.

L. E. Young was named to represent the AIME on the John Fritz Medal Board of Award for a four-year term ending in October, 1953. Attention was called to the fact that it is the turn of the AIME representatives to name a candidate for the Fritz Medal this year, and nominations are invited. Suggestions may be sent to Harvey S. Mudd, Louis S. Cates, Erle V. Daveler, or W. E. Wrather.

The sincere thanks and appreciation of the Board was voted to the San Francisco Section for its conduct of the Annual Meeting, and thirty copies of the 75th Anniversary Volume of the AIME were ordered sent to William Wallace Mein, Jr., Chairman, for distribution to committee chairmen and other active workers.

Donald H. McLaughlin Nominated for President in 1950

Donald H. McLaughlin, president of the Homestake Mining Co. and a Vice-President of the AIME, has been named to head the ticket for new Board members in 1950 by the Committee on Nominations for Institute Officers. Nominations for Vice-President are Andrew Fletcher and Robert W. Thomas, both of whom currently hold the same office, but whose present terms expire next February. The six other Directors chosen are: Francis B. Foley, superintendent of research for The Midvale Co., Philadelphia; Edward Meagher, treasurer of the Texas Gulf Sulphur Co., New York; Howard I. Young, president of the American Zinc, Lead and Smelting Co., St. Louis; Harold Decker, assistant manager of the Pan American Production, Pipe Line, and Gas Co., Houston; and C. V. Millikan, Amerada Petroleum Corp., Tulsa. Of these, only Mr. Millikan is currently a member of the Board.

Donald H. McLaughlin

At its June meeting the Board will name a ninth candidate, and if no supplementary tickets are named by Sept. 1 the above slate is automatically elected. In that case, a new Vice-President will also have to be elected by the Board, owing to the elevation of Dr. McLaughlin to the Presidency.

Where to Split the Metallurgists?

Is an operator of a cyanide plant, a copper leaching plant, a roasting plant, or a mercury distillation plant primarily a mineral beneficiator or an extractive metallurgist? The officials of the Minerals Beneficiation Division and of the new Extractive Metallurgy Division each claim these and some other similar fields, in whole or in part. The practical difficulty, so far as the AIME is concerned, is that the technical papers of the former Division are to be published in MINING ENGINEERING and of the latter in the *Journal of Metals*. Even some of the individual members immediately concerned are by no means certain as to whether they are more closely allied to the Mining or to the Metals Branches, into which the Institute is now broadly divided. A pyrometallurgist, working in a copper smelter, a field of activity not even claimed by the MBD, writes that he works in a mining district, all his friends are mining and millmen, he cannot understand and has no interest in the type of papers published in *Metals Technology*, and would like to see all smelting papers published in *Mining Engineering*. But most members of the Committee on Reduction and Refining of Copper do not appear to agree with him.

Much thought has been given to the problem but no thoroughly satisfactory solution has been found. Authors' wishes as to the medium of publication will be considered, but ultimate decision will rest with the Technical Publications Committee. For the time being, members in the controversial fields should pick the journal that they think likely to be of major interest to them, and then watch the list of all technical papers published. If they note one in which they are interested published in a journal to which they do not subscribe, they can obtain a copy for 75 cents. Fortunately it does not seem likely that cases of this kind will be too numerous.

Expensive Advertising

A double-page spread in the February *Fortune* is devoted to the wonderful results that advertisers get in that magazine. Among other items is: "A page in the August issue resulted within ten days in a closed deal for 3,000 square feet of flooring." Business must be pretty bad.

New Arizona Scholarships

A grand total of twelve scholarships at the University of Arizona and eight at Arizona State College have been established for students of mining, metallurgy, and allied fields by the Phelps Dodge Corp. One first year scholarship will be given each year at the State College, and during the first year, comparable grants will be set up for the second, third, and fourth years. The plan at the University of Arizona is the same, but double the number of awards will be made, and graduate studies are also included. Eligibility is limited to Arizona residents.

Paul G. Hoffman to Speak at ISD May Dinner

Paul G. Hoffman, ECA administrator, will be the speaker at the annual Iron and Steel Division May dinner on May 25, his subject, The ECA and You. The dinner will be held at the Statler Hotel in the Georgian Room at 7 p.m., preceded by a social hour in the foyer to the Georgian Room. Tickets are $6. Please make reservations through the Secretary of the ISD, AIME, 29 West 39th St., New York City 18.

Correction, Please

We received the following letter from R. G. Knickerbocker, chief, Rolla branch, metallurgical division, Bureau of Mines. We wish we could accept Mr. Knickerbocker's kind explanation of the error, but fear that our printer might get angry and any way we were brought up to be relatively honest.

"In the interest of the manganese industry, and especially the Electro Manganese Corp. at Knoxville, Tenn., I believe it will be necessary to correct the printer's mistake made in the fourth paragraph of the second column on page 97 under electrolytic manganese. (March Annual Review on Ferroalloy Metals.) The price of elec-

trolytic manganese effective Jan. 1, 1949, has been reduced to $0.28 per lb and not to $1.28 per lb. No doubt this is perfectly clear to those technically concerned with the manganese industry but to a great many others concerned with the critical status of treatment of low-grade domestic manganese ores this figure of $1.28 might be extremely misleading."

1949 Annual Banquet Souvenirs

The miniature gold pan, made of sterling silver, commemorating the discovery of gold in California, has caught the eye of many a member.

The pins were presented to all ladies attending the 1949 banquet in San Francisco.

Any member interested may secure one of these pins at a cost of $1.50.

Pins in 18 kt. gold, as well as in platinum, may be had at special prices.

To order, direct request and check to:

MR. H. A. SAWIN,
Yuba Manufacturing Co.,
San Francisco 4, Calif.

New York Ladies to Entertain Husbands

The members of the New York Section of the Woman's Auxiliary to the AIME will entertain their husbands on the evening of Friday, May 13, at the Engineering Woman's Club, 2 Fifth Ave. Cocktails will be served at 6 p.m., followed by dinner and entertainment, all for $3.50 per person.

Among the Student Associates

Louisiana State University

The Student Chapter at LSU has been reactivated, following a wartime cessation of activity. The first meeting, on Feb. 24, was attended by almost 300 students and business men, who heard Francis Anderson, of the Halliburton Oil Well Cementing Co., Duncan, Okla., speak on the use of plastics in unconsolidated sands. The Chapter's officers are James W. Law, President; Jack Simpson, Vice-President; and Jerry Shea, Secretary-Treasurer. H. F. Winham of the Shell Oil Co., Donaldsville, La., has returned as industrial advisor.—*Mahlon F. Manville, Corresponding Secretary.*

Lafayette College

The popular "Story of an Ore Sample" was one of three films shown at the Feb. 22 meeting of the John Markle Society. The Goodrich Rubber Co. contributed "On the Way Out," a film on the use of conveyor belts on coal mines; and the production and use of coal were presented in the last film.

Professor Leist of Lehigh University was there to interest members in the AIME Lehigh Valley Section's essay contest. Sixty of the Society's membership of 75 attended the meeting, later enjoyed refreshments in the ore dressing room.—*J. Siergiej, Secretary.*

University of New Hampshire

Four years of experience with a geophysical crew in the West were presented before the University of New Hampshire's Student Chapter at the January meeting by Harold E. Webster, Jr., geology instructor at the university. Many of the Chapter's June graduates hope to take further courses in oil geology, and so Mr. Webster's discussion of methods, equipment, the work of crew members, and the advantages and disadvantages of this type of work was particularly beneficial to them.

Geologic problems and methods in coal mining, as well as labor problems in the industry, were incorporated in a slide-illustrated talk on coal mining by Ralph Meyers, our Student Chapter's Faculty Advisor, at the February meeting. Professor Meyers' talk emphasized the vast importance of coal in our economy, noting that the petroleum field tended to have a greater place in present day news.—*Marston Chase, Corresponding Secretary.*

University of Southern California

Archibald M. Laurie was elected President of the Student Chapter at USC during the Feb. 16 meeting. Supporting him are Vice-President Richard S. Davis; Secretary Robert J. Fernandes, and Treasurer Robert R. Shaffer. The membership and program committees are headed by Richard Davis and Richard Brazier, respectively. John P. McGriff is the Chapter's parliamentarian.—*Carrol M. Beeson.*

University of Wisconsin

Not nuts and bolts, but a complete delectable dinner, was prepared in the University's metallurgical laboratory furnaces for the Mining Club's February dinner and business meeting. Steeled by their metallurgical meal, the members went on to make plans for St. Patrick's Day observances.

Snow art sculptured by the Mining Club at Michigan College of Mining and Technology took first prize at the winter carnival. The scene commemorates the '49 Gold Rush.

The repast was served at the school's new foundry, and guest speaker Chester V. Nass grasped a fine opportunity to review the past and present in foundries and outline some of the engineering problems extant in that field. Mr. Nass, vice-president of the Pettibone Mulliken Corp., Chicago, and Student Counselor for the Chicago Section, AIME, also reviewed labor-management relations in his industry, and sounded an optimistic note for future job-seekers.—*Arnold D. Arnaut, Public Relations.*

Yale University

Richard J. Christine and I. J. Hook, both of the American Brass Co., addressed the Yale Metallurgical Society on Dec. 2 and Feb. 15, respectively. Mr. Christine told members what industry expects of newly graduated metallurgists; Mr. Hook discussed Anaconda copper production in Montana, and showed a movie on the subject. Discussion periods followed both meetings and proved to be of considerable worth to the students. —*Voluntine T. Potter, Secretary.*

What Went on at Recent Local Section Meetings

SECTION	DATE	PLACE	PRESIDING OFFICER	ATTENDANCE	SPEAKER, AFFILIATION, AND SUBJECT
Arizona, Morenci Subsection	Mar. 7	Longfellow Inn, Morenci	L. O. Ormsby	30	L. L. McDaniel, mill superintendent, Phelps Dodge Corp., on AIME Annual Meeting. L. O. Ormsby, mine superintendent, Phelps Dodge Corp., on trucks for mine haulage.
Black Hills	Mar. 24	Lead, S. Dak.	Fremont Clarke	52	Fremont Clarke, Lithium Corp. of America, on AIME Annual Meeting.
Boston	Mar. 7	Smith House, Cambridge	George P. Swift	48	Frank R. Milliken, National Lead Co., on Ilmenite, Titanium Dioxide and Titanium. Carle R. Hayward, MIT, on R. H. Richards—reminiscences.
Chicago	Feb. 2	Chicago Bar Association	L. R. Berner	125	S. J. Creswell, Carnegie-Illinois Steel Co., on developments in the Bessemer Process.
Chicago	Mar. 2	Chicago	H. A. Herder	54	J. R. Van Pelt, Jr., Battelle Memorial Institute, on tools for modern prospectors.
Colorado	Feb. 23	University Club, Denver	M. I. Signer	34	M. I. Signer, Dean, Colorado School of Mines, on mineral industry education.
Columbia	Mar. 4	Davenport Hotel, Spokane	Howard P. Sherman	24	C. Y. Garber, chairman, Columbia Section, AIME, on AIME Annual Meeting.
Detroit	Mar. 21	Detroit	Frederick P. Bens		Harold Hunsicker, Aluminum Co. of America, on precipitation hardening in aluminum alloys.
Detroit	Feb. 21	Detroit			R. K. Hopkins, M. W. Kellogg Co., on the Kellogg Process of ingot production.
El Paso Metals	Mar. 9	Hotel Cortez, El Paso	E. M. Tittman	26	F. E. Hewitt, asst. prof. of education, Texas Mines and Met., film taken in Russia, 1936.
Gulf Coast	Feb. 15	YMCA, Houston	E. B. Miller, Jr.	122	Olin G. Bell, Humble Oil Co., on deep drilling in the Gulf Coast area.
Lehigh Valley	Dec. 6	Bethlehem, Pa.	M. L. Fuller	104	W. E. Wrather, director, USGS, on recent trip to the Near East.
Mid-Continent	Mar. 14	Bartlesville, Okla.	John P. Hammond	151	Herman H. Kaveler, Philips Petroleum Co., on cases of increasing well densities.
Montana	Mar. 1	Butte	J. Hollis McCrea		H. G. Satterthwaite, Anaconda Copper Mining Co., on the AIME Annual Meeting.
North Pacific	Feb. 17	Rose's Highway Inn, Seattle	W. C. Leonard	39	H. K. Benson, emeritus professor of chemistry, Univ. of Washington, on agricultural production problems.
North Pacific	Mar. 17	Rose's Highway Inn, Seattle	Kenneth Anderson	48	J. Harveson, Standard Oil Co., of California, motion pictures, "Desert Venture"; "City of Destiny"; "Winter Olympiad."
Oregon	Jan. 21	Nortonia Hotel, Portland	Hollis Dole	23	William E. Caldwell, Oregon State College, on northwest strontium mineral deposit.
Oregon	Feb. 25	Mallory Hotel, Portland	Hollis Dole	22	James H. Jensen, Pacific Carbide and Alloys, on calcium carbide for Pacific northwest industries.
Oregon	Mar. 18	Mallory Hotel, Portland	Hollis Dole	31	Pierre R. Hines, consulting engineer, on conveyors and materials handling.
Pittsburgh	Mar. 7	Mellon Institute of Industrial Research	Stephen Krickovic	300	C. H. Snyder, president, Sunnyhill Coal Co., on Colmol continuous mining machine.
Southern California	Feb. 18	Los Angeles	E. O. Slater	70	Richard W. Smith, U. S. Chamber of Commerce, "Government in Your Hair."
Southwest Texas	Mar. 9	Corpus Christi	Houston Parrish	166	George Howard, Stanolind Oil & Gas Co., on proper cementing of casing.
St. Louis	Feb. 18	Hotel York	H. A. Neustaedter	52	Frank G. Breyer, Singmaster & Breyer, on exporting American know-how.
Utah	Feb. 24	Salt Lake City	J. C. Landenberger, Jr.	56	C. J. Christensen, Dean, School of Mineral Industries, University of Utah, on prospectors and Indians. Elroy Nelson, Univ. of Utah, on local taxation in mining industry.
Utah	Mar. 17	Newhouse Hotel, Salt Lake City	J. C. Landenberger, Jr.	44	D. C. Houston, Kennecott Copper Co., "Personnel is People."

Current Institute Papers

The following papers are available to Institute members in the three journals. Each member will receive one classification in the journal of his choice. Members may obtain papers in the two remaining classifications by purchasing the indicated issue of the journal at $0.75 per copy. There are no separate copies of the individual papers. ME means Mining Engineering, JM Journal of Metals, and JPT Journal of Petroleum Technology.

Mining Papers

The Heavy Mineral Deposits of the East Coast of Australia—By N. H. Fisher. (*November Mining Technology.*)

Underground Anemometry — By C. M. Smith. (*January Mining Engineering.*)

Beneficiation of Industrial Minerals by Heavy-media Separation—By G. B. Walker and C. F. Allen. (*January Mining Engineering.*)

Importance and Application of Piezo-Electric Minerals—By Hugh H. Waesche. (*January Mining Engineering.*)

Texas White Firing Bentonite—By F. K. Pence. (*January Mining Engineering.*)

The Application of Screening and Classification for Improved Fine Anthracite Recovery—By W. Julian Parton. (*February Mining Engineering.*)

Operational Statistics of a Marion 5560 Power Shovel—By G. B. Clark and G. L. Reiter. (*February Mining Engineering.*)

The Flotation of Copper Silicate from Silica—By R. W. Ludt and C. C. DeWitt. (*February Mining Engineering.*)

Recent Trends in Asbestos Mining and Milling Practice—By M. J. Messel. (*February Mining Engineering.*)

A Technical Study of Coal Drying—By G. A. Vissac. (*February Mining Engineering.*)

Metals Papers

Transient Plastic Deformation—By R. P. Carreker, J. G. Leschen, and J. D. Lubahn. (*September Metals, Technology.*)

Oxide Films Formed on Metals and Binary Alloys. An Electron Diffraction Study—By J. W. Hickman. (*December Metals Technology.*)

Development of the Modern Zinc Retort in the United States—By H. R. Page and A. E. Lee, Jr. (*February Journal of Metals.*)

The Effect of Strain-temperature History on the Flow and Fracture Characteristics of an Annealed Steel—By E. J. Ripling and G. Sachs. (*February Journal of Metals.*)

Relation Between Chromium and Carbon in Chromium Steel Refining—By D. C. Hilty. (*February Journal of Metals.*)

The Densification of Copper Powder Compacts in Hydrogen and in Vacuum—By Charles B. Jordan and Pol Duwez. (*February Journal of Metals.*)

Influence of Composition on the Stress-Corrosion Cracking of Some Copper-base Alloys — By D. H. Thompson and A. W. Tracy. (*February Journal of Metals.*)

Calendar of Coming Meetings

MAY

2 Pittsburgh Section, AIME. President L. E. Young.
2 Boston Section, AIME.
2-4 ASME spring meeting, New London, Conn.
2-5 American Foundrymen's Society, 53rd annual meeting, St. Louis.
5 Reno Branch, Nevada Section, AIME.
6 Columbia Section, AIME.
6-7 American Institute of Chemists, annual meeting, Chicago.
7 Chicago Section, AIME. President's Night.
8-12 AICE, Tulsa, Oklahoma.
9 Mid-Continent Section, AIME.
9-12 American Mining Congress, coal convention and exposition, Public Auditorium, Cleveland.
10 East Texas Section, AIME.
11 El Paso Metals Section, AIME.
11 San Francisco Section, AIME.
11-13 Engineering Institute of Canada annual meeting with International Management Congress hemisphere meeting, Chateau Frontenac, Quebec.
14 Northwest Industrial Minerals Conference under auspices of Columbia Section, AIME, Spokane.
16 Detroit Section, AIME. A. A. Cooley on metallic sheet.
May 16-June 3 U.N. Scientific Conference on Conservation and Utilization of Resources, New York.
17 Gulf Coast Section, AIME.
17 Washington, D. C., Section, AIME.
18 Southwest Texas Section, AIME.
19 Carlsbad Potash Section, AIME.
19 North Pacific Section, AIME.
19 Utah Section, AIME.
19-20 Lake Superior Mines Safety Council, Duluth, Minn.
20 Oregon Section, AIME.
23 Alaska Section, AIME.
24 Montana Section, AIME.
25 Iron and Steel Division, AIME, annual May dinner, Statler Hotel, New York City.
25-26 American Iron and Steel Institute, general meeting, New York City.

JUNE

3-4 Central Appalachian Section, AIME, spring meeting, Blacksburg, Va.
5-10 SAE, summer meeting, French Lick Spring, Ind.
16 Engineering Foundation, 29 W. 39 St., New York City.
June 27-July 1 ASTM, 52nd annual meeting, Chalfonte-Haddon Hall, Atlantic City, N. J.
20-22 American Society of Heating and Ventilating Engineers, semi-annual meeting, Minneapolis, Minn.
20-24 AIEE, summer general meeting, New Ocean House, Swampscott, Mass.
20-24 National Society for Engineering Education, RPI, Troy, N. Y.
25-26 American Iron and Steel Institute, general meeting, N. Y. C.
27-30 ASME, semi-annual meeting, San Francisco.

JULY

9-23 Fourth Empire Mining and Metallurgical Congress, Great Britain.
13-15 American Society of Civil Engineers, summer convention, Mexico City.
15-24 Pan-American Engineering Congress, Rio de Janeiro.

AUGUST

23-26 AIEE Pacific general meeting, Fairmont Hotel, San Francisco.
26-Sept. 10 Engineering & Mining Exhibition, London, England.

SEPTEMBER

25-28 Regional Meeting, AIME, Neil House, Columbus, Ohio.
25-28 American Mining Congress, Western fall meeting, Spokane.
29-30 ASME, fall meeting, Erie, Pa.
29-Oct. 1 Colorado School of Mines, 75th anniversary celebration.
Sept. 30-Oct. 1 Southern Ohio Section of Open Hearth Committee, AIME, fall meeting, Deshler-Wallick Hotel, Columbus.

OCTOBER

5-7 Petroleum Branch, AIME, fall meeting, Plaza Hotel, San Antonio, Texas.
17-19 Institute of Metals Division, AIME, fall meeting, Allerton Hotel, Cleveland.
17-23 AIEE, 1949 Mid-West meeting, Netherlands-Plaza, Cincinnati.
20-21 Petroleum Branch, AIME, Elks Club, Los Angeles.
26-27 Joint Fuels Conference, ASME-AIME, French Lick Springs Hotel, French Lick, Ind.
28 Pittsburgh Section of Open Hearth Committee and Pittsburgh Section, AIME, annual fall meeting, William Penn Hotel, Pittsburgh.

NOVEMBER

1-5 Pacific Chemical Exposition, California Section, American Chemical Society, San Francisco Civic Auditorium.
2-4 American Society of Civil Engineers, fall meeting, Washington, D. C.
7-10 AIChE, annual meeting, Pittsburgh, Pa.
9-11 Industrial Minerals Division, AIME, Tampa, Fla.
12-14 Geological Society of America, annual meeting, Hotel Cortez, El Paso.

DECEMBER

8-10 Seventh Annual Conference, Electric Furnace Steel Committee, Iron and Steel Division, AIME, Hotel William Penn, Pittsburgh.

FEBRUARY 1950

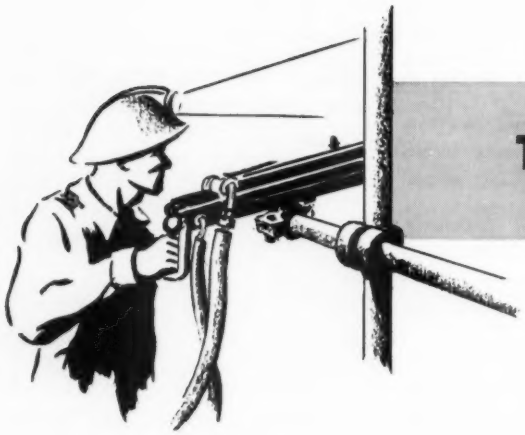
12-16 Annual Meeting, AIME, Statler (Pennsylvania) Hotel, New York City.

APRIL 1950

10-12 Open Hearth Conference, and Blast Furnace, Coke Oven and Raw Materials Conference, Netherland-Plaza Hotel, Cincinnati.

DECEMBER 1950

7-9 Eighth Annual Conference, Electric Furnace Steel Committee, Iron and Steel Division, AIME, Hotel William Penn, Pittsburgh.



THE DRIFT OF THINGS

. . . as followed by EDWARD H. ROBIE

For Peace or War?

Unquestionably, the North Atlantic Pact is an important milestone in international agreements destined to prevent war, but whether or not it will be more effective than previous treaties remains to be seen. The approach is quite different from the Briand-Kellogg treaty—the Pact of Paris—signed by fifteen nations in 1928, and subscribed to by others including Russia later. That was an out-and-out renunciation of war, which certain of the signers, notably Germany and Japan, did not take seriously, as subsequent events proved. A different type of agreement designed to prevent war was that embodied in the League of Nations, and the Permanent Court of International Justice, and latterly in the United Nations. A weakness in the last-named, of course, is the privilege of the veto power, which both Russia and the United States insisted on reserving and which Russia has used to excess. No joint action, such as the United Nations agreement implies, can work if one nation reserves the right to prevent action in cases where its own interests are involved. Another weakness is lack of police power to enforce its decisions. Thereby it can become little more than an international debating society. The world government movement, as is being conducted with some success by United World Federalists, would seem to be a much more realistic means of preventing war. Soviet Russia will have none of it, but might subscribe to it if the rest of the world did.

Heretofore military alliances have been notably unsuccessful in preventing war, as have all other means, but at the present juncture in world affairs, with Soviet imperialism rampant, some forceful repressive measures seem necessary. Russia has long shown an unco-operative spirit with the rest of the world. Appeasement gives no promise, having failed so signally with another totalitarian government imbued with the idea of re-forming the world.

The North Atlantic Pact might better serve its purpose of scaring off aggressors, and preventing war, if more nations joined it. We already have the treaty of Rio de Janeiro, signed in 1947, whereby the American nations pledge themselves to unite against any one that starts a war. This would seem to fit in with the new pact. If, now, all the rest of the world would enter into such a treaty and aggression were sharply defined, then the force that the United Nations lacks to back up its decisions would be provided and a large part of the aims of the world government advocates would be realized.

Russia's opposition to the present pact means one of two things—either that she herself has designs on still more neighboring countries, or that she doubts that the pact is designed merely to stop aggression. In view of her inexcusable attack on Finland before World War II, and her seizure of control of Czechoslovakia after the war, to cite but two examples, one may be pardoned for considering the first reason the paramount one.

Therefore, a military alliance against aggression, such as the North Atlantic pact, seems well justified at the present time and likely to be a deterrent to war, even though it may not prevent one. But the entire world should join such a pact—and then live up to it. In other words, the United Nations with a gun in its pocket.

We have no sympathy whatever with the minority that think Russia will do as she pleases as soon as she gets the atomic bomb and that therefore we should dispose of her as soon as possible. Not only would that be morally reprehensible, but the practical result of another war so soon after the last might easily be the overthrow of our system of government. It has already been undermined by two disastrous world wars, and if we cannot prevent another, then it is high time something different should be tried. Not that Communism gives hope of being anything better.

The best rule for the present, as we see it, is that to which Theodore Roosevelt gave voice: "Speak softly but carry a Big Stick." The Big Stick in this case is the North Atlantic Pact, with the requisite power to carry it out.

Encouragement for Our Teachers

Winston Churchill, in his fine address given at the Mid-Century Convocation of MIT, paid a well-deserved tribute to our American engineering schools: "We have suffered in Great Britain by the lack of colleges of university rank in which engineering and the allied subjects are taught. Industrial production depends on technology and it is because the Americans, like

the prewar Germans, have realized this and created institutions for the advanced training of large numbers of high-grade engineers to translate the advances of pure science into industrial technique—it is for that reason that their output per head and consequent standard of life are so high."

He might have added that for the same reason this country was the first to produce enough fissionable material to make possible the practical use of nuclear energy.

Our engineering schools have long been the target of critics who have complained of inadequate training. This view of a foreign observer should give the schools much encouragement.

Dr. Boyd Confirmed As Director

Mining men were glad to hear that Jim Boyd had finally been confirmed as director of the Bureau of Mines and no longer had to serve without a salary. In fact, we understand that his back salary is to be paid. Unfortunately, the directorship of the Bureau has for some years depended more than it should on politics. But fortunately Dr. Boyd is a comparatively young man, and able professionally, so perhaps, with a good record behind him, he can survive any change in the political complexion of the Administration, should one ever occur.

The delay in confirming Dr. Boyd as director is said to have been due to the opposition of John L. Lewis, who has no use for Secretary Krug, Dr. Boyd's boss. John L. was also able to bring political influence on Senator Millikin, of Colorado, who long was able to block the appointment but was finally overruled in the new Administration. When Lewis called the two-week strike of the coal miners, purportedly to call attention to the need for safer working conditions, the matter was brought to a head, and the Senate confirmed Dr. Boyd partly to show its independence of Lewis. Even so, eleven Senators voted against the appointment, with fifty favoring it. Perhaps the names of the eleven should be remembered. They were: Millikin, of Colorado, Brewster of Maine, Bricker of Ohio, Capeheart and Jenner of Indiana, Langer of North Dakota, Schoeppel of Kansas, and Wherry of Nebraska, all Republicans; with Johnson of Colorado, and Kilgore and Neely of West Virginia, Democrats.

The principal argument offered against Dr. Boyd was that he had not had operating experience in mining, and had had no contact with either the coal mining industry or with health and safety matters. Operating experience would not appear necessary to fill the job acceptably; and men with both coal and metal-mining experience combined with health and safety training are exceedingly rare.

The Accident Record

The real reason for the two-week shutdown of the coal mines was probably not so much as a memorial to coal miners who had been victims of 55,000 coal-mine accidents last year, as alleged, as it was to reduce the stocks of coal a bit, so as to afford better bargaining conditions when the time for setting a new contract comes up, on May 1. The shutdown had little practical effect, for coal demand has recently been much less than capacity, so that a large number of the miners have been working only two to four days a week. Were wages lower, which would permit lower coal prices, then more coal in relation to oil would be used, and it might be that the income of coal miners would be greater than at present. But high wages make the best selling point, even though the opportunity to get them is limited.

If the reason for the shutdown was really the one given, then the timing was not particularly propitious, for the news came out during the strike that in 1948 there were fewer accidents per ton of coal mined than in any previous year in history. As to fatalities, the record was not quite so outstanding, but still good: it was the fourth lowest year as to deaths in bituminous mines and the second lowest in anthracite mines. For both branches, 1010 men were killed last year and 54,100 injured. That is still not a record to be proud of, nor is the record of work injuries for all industries. Last year disabling work injuries amounted to 1,960,000, deaths 16,500, permanent disablements 1800; with 41,000,000 man-days of work lost, representing more than four billion dollars in wages. Automobile fatalities were around 32,000.

It's dangerous to be alive. Carelessness takes a bigger toll of life and health than war but is not nearly so costly in money.

AS&R's Golden Anniversary

On April 4 the American Smelting and Refining Co. celebrated its fiftieth anniversary. Receptions and entertainment were features of the day at many of its plants, and the employes of the headquarters office in New York were entertained at the Bankers' Club. Though the words "mining" and "milling" are not included in its name, its activities include these fields as well, and extend all over the world.

We have been visiting AS&R plants, and have been on friendly terms with AS&R men, for 35 years. We have found the plants well run by a fine lot of men who have been uniformly most generous and hospitable when we dropped around. Until we decided it was more important to buy a home than to be an AS&R stockholder we used to receive regular dividends, of modest amount but an excellent return on our small investment. AS&R men have written innumerable papers for the AIME, and have served on numerous committees, and in various capacities as officers. One is currently a Director.

The Company produces practically all nonferrous metals, to some extent at least, but is important in copper, lead, zinc, gold, and silver. Its interests are in both primary and secondary metals, and extend to fabricating. It operates several coal mines but so far as we know has kept out of the oil business. Much of its raw material is purchased from small shippers but much smelting and refining is done for large companies too, like Kennecott, for instance.

So we add our salute to the others that AS&R has received. For half a century it has conducted important units in a basic American industry with conspicuous success to itself and to its stockholders, and in a highly creditable manner as a national institution. May the next half century add further to its stature.

News of AIME Members

Wayne J. Ahl is a junior engineer with the Inland Steel Co. His address is 336 W. Division St., Ishpeming, Mich.

L. W. Allen, on six months' leave from his post as underground manager of Nchanga Consolidated Copper Mines Ltd., Chingola, N. Rhodesia, spent the first three months of that leave traveling some 6000 odd miles, doing a little fishing here and there, taking in the bright lights of Johannesburg and one or two other cities in S. Africa, and is spending the last three months on his farm, quite close to the coast in a beautiful part of South Africa. The fishing is good, and with the farm to potter about on, he expects to enjoy himself. Nchanga Consolidated is still busy with an expansion program and has a big construction and development program on hand. The tonnage mined has been steadily increasing and just before he left had reached a record of some 114,000 tons a month. The first increase in capacity is designed to handle 150,000 tons a month, but it looks as if the plant will have a rather larger capacity than that for which it was designed.

Edgar F. Andersen, formerly with the Golden Queen Mining Co., is now working for the Calaveras Cement Co., San Andreas, Calif.

Alfred L. Anderson, professor of economic geology at Cornell University, Ithaca, N. Y., is spending his Sabbatical leave of absence in the spring term visiting mining camps in the Rocky Mountain region.

Lloyd E. Antonides receives his mail at 13 Church St., Franklin, N. J. He is surveyor for the New Jersey Zinc Co.

Florentino B. Baca has been plant manager of the Hardsocg Mfg. Co., manufacturers of power driven rotary drilling equipment and miners tools and supplies, a subsidiary of the Cardox Corp. of Chicago, since November, 1947. He lives at 718 W. 4th, Ottuma, Iowa.

Wayne O. Axtell

Wayne O. Axtell, Colonel in the Corps of Engineers, has retired from the Army after a final tour of duty in the Pacific. He is now located as an engineer in the office, Chief of Engineers, Washington, D. C.

W. R. Allen

W. R. Allen is chairman of the board of directors of the Bostana Mines Co. and consultant for Elkhorn Beaverhead Mines Co. He has on the press, ready for distribution, a story of western development and particularly early day mining history in Montana with a backdrop of national events and personalities.

Howland Bancroft, mining consultant, of New York, who has spent the past eighteen months on professional work in South and South West Africa with headquarters in Tsumeb, returned to the States early in March. He will be engaged in an investigation in this country for the next few months, following which he will return to South Africa about mid-year, with headquarters in Johannesburg.

Robert W. Barnes can be reached at 506 Nancy St., Charleston, W. Va. He is employed by the Warner Collieries of Mammoth, W. Va.

Henry E. Bartony, Box 231, Nellis, W. Va., is employed in the engineering department of the Armco Steel Corp.

Andre C. Beguin, who had been a student at the University of British Columbia, is mill engineer for Torbrit Silver Mines, Ltd., Alice Arm, B. C.

Charles H. Behre, Jr., vice-president of Behre Dolbear and Co., New York City, left the States recently for Burma. The Company has been appointed general consultants and technical advisers on minerals for the Burmese Government. Dr. Behre will make his headquarters at Rangoon and prepare recommendations outlining the scope of industrial and mining rehabilitation.

John R. Bogert is employed as a field geologist by the Bethlehem Steel Co., and is addressed in care of W. A. Rankin, construction superintendent, Iron Mines Co. of Venezuela, San Felix, Est. Bolivar, Venezuela.

John P. Bowman is employed by the Foster Wheeler Corp., Carteret, N. J., as a service engineer.

W. A. Broughton is head of the geology department at the Wisconsin Institute of Technology, Platteville, Wis. His address is 225 Bradford, Platteville.

Donald M. Brown is working with the U. S. Geological Survey, estimating coal reserves. His address is 19th and F Sts., FWA Bldg., Washington 25.

Frank A. Burns, who was a student at Lehigh University, is working for the Bethlehem Collieries Corp., Johnstown, Pa., as a junior engineer. His mailing address is Box 62, Ellsworth, Pa.

John L. Beach is chief engineer-geologist in charge of exploration for Rhodesia Copper Ventures Ltd., P. O. Sinoia, S. Rhodesia.

E. L. Beck and his associates have taken over the operation of the Perch hydraulic mine at Orleans, Calif.

Edward J. Bottomley is superintendent of the Sunlight Coal Co., Boonville, Ind. He was with the Tecumseh Coal Corp.

Harold L. Brandt has taken the post of assistant engineer with the Pend Oreille Mines and Metals Co., Metaline Falls, Wash. He had worked in Chihuahua, Mexico, for the American Smelting and Refining Co.

Willis F. Bronkie is vice-president and secretary of the Rising & Nelson Slate Co., West Pawlet, Vt. He has been sales engineer for the Victaulic Co. of America.

Alan D. Brown, graduated from the University of Minnesota School of Mines last June and is now employed by the Anaconda Copper Mining Co. in Butte, Mont.

David W. Boise, formerly of Hurley, N. Mex., where he was working with the Kennecott Copper Co., now lives at 917 West St., Silver City.

Franklin W. Butterfield has transferred from the University of Nevada to the Placer College, School of Mines, Auburn, Calif. He is employed part time by the Empire Star Mines Co. and receives mail at P. O. Box 817, Grass Valley, Calif.

Sam S. Coldren has resigned from the Acoje Mining Co., Santa Cruz, Zambales, to become manager of the Misamis Chromite Co., Na-awan, Initao, Misamis Oriental, P. I. The Company is operated by International Engineering Co. Warner-Barnes.

Alden P. Colvocoresses writes from Box 537, Superior, Ariz., that he has taken over and is maintaining the files of his late father, **George M. Colvocoresses.** These files contain reports and data on approximately 1000 different mining properties in Arizona and adjacent states.

Annan Cook has given up his post as chief geologist to Frobisher Ltd., in Africa, and has accepted a job in the exploration department of the Kennecott Copper Corp.

Boyd Appointment Confirmed

James Boyd's appointment as director of the Bureau of Mines was confirmed by the Senate on March 22 by a vote of 50 to 11. Here he is sworn in by Chief Clerk Dotson as Secretary of the Interior J. A. Krug looks on. The former dean of the Colorado School of Mines took this post in August, 1947, and received pay for about four months until a short session of Congress adjourned in December of that year without confirming him. John L. Lewis, president of the United Mine Workers, who had been blocking confirmation for more than two years, was mentioned only once in the hour-long debate in the Senate and the coal mining stoppage called by Mr. Lewis, partially in protest against Dr. Boyd's appointment, was not mentioned at all.

Ronald Crawford lives at Apt. D., 2509 Park Lane Court S., Mountain Brook, Ala., while he works for the Equipment Service Co., Birmingham, as a sales engineer.

W. H. H. Cranmer, president and general manager of the New Park mining Co. of Keetley, Utah, succeeds **James Ivers,** vice-president and general manager of the Silver King Coalition Mines Co., as president of the Utah Mining Association.

L. A. Dahners has traveled from Anchorage, Alaska, to Skouriotissa, Nicosia, Cyprus, and can be reached there in care of the Cyprus Mines Corp.

James R. Diehl is now employed in the technical department of the engineering and construction division of the Koppers Co. at Pittsburgh. His home is at 409 N. Neville St., Pittsburgh 13.

Ira F. Davis, who is a consulting mining engineer, is now living on Meadville Dr., in Onancock, Virginia.

Byron M. Emery recently graduated from the Pennsylvania State College with a B.S. degree in mining engineering and is employed by the Atlas Powder Co., Wilmington 99, Del., as a technical representative.

John W. England is assistant geologist for the Colorado Fuel and Iron Corp., Pueblo, Colo. His address in Pueblo is Apt. 604-K Air Base.

Harry J. Evans, mining engineer of the Pierce Management staff in Scranton, Pa., left for Korea on March 9 to study the economic potentialities of four coal fields in southern Korea.

A. L. Fairley, Jr., has been made assistant to the president of the Snyder Mining Co. which operates three iron mines on the Mesabi range of Minnesota.

John H. Ffolliott, formerly with the Tennessee Copper Co., is now with the Miami Copper Co., Rm. 1824, 61 Broadway, New York City 6.

John W. Foreman is working for the Monroe Coal Mining Co., Revloc, Pa., as a junior mining engineer.

Edward S. Frohling, after graduating from MIT, worked for a brief period as research engineer for the Division of Industrial Co-operation there. He is now employed by the Climax Molybdenum Co. as a metallurgical testing engineer.

Raymond B. Gallant is now with E. I. du Pont de Nemours & Co. in the explosives sales division. He represents the Company out of the Denver, Colo., office and covers northeast Wyoming and central Montana.

Conrad I. Gardner has gone to Potosi, Bolivia, as engineer for Cia. Minera Unificada del Cerro de Potosi, Casillas 30 y 52.

P. W. Gifford, Jr., who had been general mine foreman for the Lone Star Steel Co., is now superintendent of the slag crusher of Gifford-Hill & Co., Daingerfield, Texas.

B. E. Grant, since 1944 general superintendent of the U. S. and Lark mine of the U. S. Smelting Refining and Mining Co., has been promoted to assistant to the manager of Western mines succeeding **A. G. Kirkland** who became assistant manager of Western mines on Jan. 1. **M. M. DuBois** has been made general superintendent of the U. S. and Lark mine and **Harold H. Wells,** former assistant general mine foreman of the U. S. section, has become assistant superintendent of the Lark section.

Allen D. Gray, Jr., is taking the training program of the Rochester & Pittsburgh Coal Co., Indiana, Pa. His address is 1058 Church St., Indiana.

William A. Griffith and **William A. Griffith** were mixed up in a personal item in the March issue. The former is an instructor at MIT, with an address at 81 Marion St., Brookline, Mass., while the latter is a student at the University of Idaho, Moscow, according to our records. We apologize to the Mr. Griffiths and hope our error has caused them no inconvenience.

F. W. Goddard has been transferred by the AS&R Co. from their Avalos mill unit at Chihuahua to their Parral unit at Parral, Chih., Mexico, in the same post of assistant mill superintendent. The Parral mill produces concentrates of lead, zinc, and copper, milling 1500 tons a day.

Mostyn G. Grant is working for the Coronado Copper and Zinc Co., Los Angeles. His home is at 2031 Pelham Ave., West Los Angeles.

Harry G. Grigsby, former Missouri School of Mines student, is working for the Idarado Mining Co. at Ouray, Colo.

Ivan D. Hagar retired from the Titanium Division of the National Lead Co. last May and moved to R. F. D. 2, Middlebury, Vt. He is retained by National Lead as a consultant.

D. F. Hewitt has left the University of Wisconsin and joined the Ontario Department of Mines staff, Parliament Bldg., Toronto 2, Ont.

Arthur Horen, formerly assistant geologist for the Lone Star Steel Co., is now pursuing graduate study in geology at Harvard. His new address is 27 Maple Ave., Cambridge 38, Mass.

Roy Hatch, labor relations director at the Utah Copper Division of the Kennecott Copper Corp., has been advanced to assistant to the general manager with jurisdiction over all employe and public relations. **L. F. Pett,** assistant mine superintendent, has been made mine superintendent, and **J. C. Landenberger, Jr.,** formerly general mill foreman, replaces Mr. Hatch as director of labor relations.

George Deike and Eugene Jones

Eugene H. Jones, majoring in coal mining engineering at the University of Pittsburgh, received the Old Timers Club award from **George H. Deike,** president of Mines Safety Appliances Co. The Old Timers Club, a social organization of leading coal mining executives, recently decided to give prize awards to outstanding seniors majoring in coal mining engineering at several schools of mines. On Feb. 10 Mr. Deike awarded a gold watch to Mr. Jones, whom a committee had decided upon as outstanding in scholarship, character, and promise. The watch was engraved "Old Timers Club Award to Outstanding Senior Student, Eugene H. Jones, University of Pittsburgh, Class of 1949, Coal Mining Engineering."

F. S. McNicholas and Mrs. McNicholas

F. S. McNicholas returned to Denver the first of April following a month of consulting work on block caving methods at the Mufulira Copper Mines property in Northern Rhodesia. He was accompanied by Mrs. McNicholas.

A. L. Hayes, former superintendent of the Empire Zinc Co. at Hanover, N. Mex., has been transferred to the New York office of the New Jersey Zinc Co., where he will assist the general manager of mines, **S. S. Huyett** has been appointed superintendent of the Empire Zinc Co. at Hanover.

Ira K. Hearn, Jr., who was formerly works industrial engineer of ore mines and quarries for the Tennessee Coal, Iron and Railroad Co., Bessemer, Ala., has recently accepted the post of assistant to the president of the Quebec Iron and Titanium Corp., a subsidiary of Kennecott Copper. His office is at 120 Broadway and he is making his home at the Park Garden Apartments, 134-42 Franklin St., Morristown, N. J.

Arthur S. Hecht, consulting engineer of San Francisco, is now an associate of Behre Dolbear and Co., consulting mining engineers and geologists, 11 Broadway, New York City 4. Mr. Hecht recently returned from Korea and completed an assignment for the Civil Affairs Section of the Army and the ECA for Korea as a consultant, in the United States, on a research project for tungsten ore beneficiation.

Charles T. Holland has joined the staff of the mining engineering department of the Virginia Polytechnic Institute. He had been professor of mining engineering at West Virginia University. Mr. Holland succeeds **L. I. Cothern** who is head of the mining engineering department at Ohio State University.

Fred H. Howell is employed as a mining engineer and geologist with the Federal Mining and Smelting Co. at the Page mine, Page, Idaho.

Charles O. Hower is addressed at Emmett, Idaho, and works as metallurgist for the Calera Mining Co. at Forney.

Charles D. Hoyt graduated from Penn State on Jan. 31 and is now employed by the Westmoreland Mining Co. His new mailing address is 143 S. Spring St., Blairsville, Pa.

Lemuel B. Hunter has been made manager of the raw materials department of the Inland Steel Co., Chicago.

Nick Hurley has resigned his post with Cie. Aramayo de Mines en Bolivie at La Paz and can now be reached at 1510 Mathews, Fort Collins, Colo.

Robert H. Inman has taken the job of assistant engineer with the United Electric Coal Co., Chicago. Mail reaches him at 403 N. First St., Canton, Ill.

John A. Johnson is acting supervisor at the Duluth office of the Bureau of Mines.

W. Bruce Johnson is employed as a coastal analyst for the Navy Department. His address is Rm. 3A-538, Pentagon Bldg., Washington 25, D. C.

Russell C. Johnson has changed his address to in care of the Northern Peru Mining and Smelting Co., Casilla 219, Lima, Peru. He had been with Cia. Minera Asarco.

Theodore L. Johnston has resigned as metallurgist for the Bureau of Mines to do consulting work with headquarters at Hamilton, Mont.

Frederick C. Kruger, assistant chief geologist of the Cerro de Pasco Copper Corp., is on leave of absence and will be at Northwestern University, Evanston, Ill., as lecturer in geology during the winter and spring quarters.

Thomas A. King, Box 651, Clarksville, Pa., is a student engineer with the Westmoreland Mining Co., Blairsville, Pa.

Charles P. Knaebel and a partner have taken a lease from the U. S. Smelting Refining and Mining Co. on its Shingle Canyon mine, near Fierro, N. Mex. The operations consists of small scale production of zinc-lead ore.

Edward H. Kraus has been, since February, 1945, on the retired list of the University of Michigan. However, this does not mean that he is not pursuing actively mineralogical and gemological affairs. In fact, with his colleague, C. B. Slawson, they were able to bring out the fifth edition of Gems and Gem Materials in December, 1947. At present, with W. F. Hunt and L. S. Ramsdell, he is at work revising the Mineralogy and hopes to bring out the fourth edition within a year or two.

H. M. Lavender has been made a member of the board of directors of the Phelps Dodge Corp. He is vice-president and general manager of Phelps Dodge in charge of all western operations of the Corporation.

John W. Lowry is process metallurgist in the division of metallurgical research of the Permanente Metals Corp., Spokane, Wash. Mail reaches him at E. 10918 Main, Opportunity, Wash.

John R. LeGrand is working for the Atlantic Coast Line Railroad, Wilmington, N. C., as an industrial geologist.

Robert T. Macaul is working in the rock drill department of the Ingersoll-Rand Co., 11 Broadway, New York City 4.

Edward Marks, while working on his Master's degree, is a student assistant in the department of geology at the University of Texas, Austin.

Victor R. Martin lives at 642 S. Gilpin St., Denver, and during working hours is field engineer for the National Fuse and Powder Co. He moved to Denver from Butte, where he was underground engineer for the Anaconda Copper Mining Co.

Charles Gill Morgan

Charles Gill Morgan returned to Dallas, Texas, in January and has offices in the Tower Petroleum Bldg., specializing in petroleum geology and research in seismology and glaciology. After graduation from SMU, he served with the Geophysical Research Corp. and the Seismograph Service Corp., spent two years in graduate study at Harvard, and then was off to the Antarctic with Admiral Byrd as chief geologist on his second expedition. In 1936 he became associated with Herbert Hoover, Jr., as vice-president of the United Geophysical Co. in California. Called to active duty in Washington as a Captain in the Air Corps in 1941, Colonel Morgan was successively in charge of Latin American intelligence, European targets, and finally the Operational Intelligence Division for both theaters of war. As the war neared its close in Europe, he was relieved from his assignment by the War Department in Washington to serve on the USAF Evaluation Board as director of tactical air operations in Europe. He returned to inactive duty in March, 1946, and has been engaged in independent research and as consultant in Boston and New York since that time.

John F. Marley has been assistant mine superintendent with the Gouverneur Talc Co. at Balmat, N. Y., since last October. His address is 179 Rock Island St., Gouverneur, N. Y.

Richard R. Matthew, county surveyor and mining engineer for the U. S. Grant Mining Co., who lives in Virginia City, Mont., is the president of the Madison County Mining Association.

Arne A. Mattila has been appointed mining engineer of the mining branch, conservation division, U. S. Geological Survey, and will assist with the supervision of mining operations on leased government land in the Billings, Mont., district. Mr. Mattila is a graduate of the Montana School of Mines, class of 1936. His mining experience includes about seven years with the Anaconda Copper Mining Co. and three years as mining engineer with the Republic Coal Co. of Roundup, Mont.

Walter L. Maxson, vice-president of the Oliver Iron Mining Co., Duluth, Minn., has been appointed to the Atomic Energy Commission's Advisory Committee on Raw Materials. Mr. Maxson has been an officer of the Oliver company since 1944. Prior to that he was sales manager and chief engineer of the mining division of the Allis-Chalmers Mfg. Co. for seventeen years. He has also served as associate professor of metallurgy at the Colorado School of Mines, and has been connected with several mining companies in Colorado, Arizona, and Australia.

John W. Mrock transferred on Jan. 28 from the Bureau of Reclamation, Coachella, Calif., to the Navy Department, and is employed at present as a laboratory technician at the Naval Air Missile Testing Center at Point Mugu, Calif. His new mailing address is 245 W. 1st St., Oxnard, Calif.

Harvey S. Mudd, president and managing director of Cyprus Mines Corp., officer of several West Coast business organizations, and past president of the Institute, was given the Egleston medal, awarded annually by the Columbia University Engineering School Alumni Association for distinguished engineering achievement, on April 28. Mr. Mudd's principal professional activity for many years has been the development and management of important copper mines in the Island of Cyprus. From 1914 to 1926 he devoted his energies to these and other mining properties. During the many years of his connection with Cyprus Mines, Mr. Mudd has solved numerous complex mining and metallurgical problems involving mine ventilation and safety, fire hazards, and production.

Henry D. Mumper is engineer in the steam and combustion department of the Bethlehem Steel Corp., Johnstown, Pa. His mail goes to 711 Graham Ave., Windber, Pa.

John C. Murray, who has been at the Pittsburgh works of the Jones & Laughlin Steel Corp., has joined the staff of the Republic Steel Corp. at Youngstown, Ohio.

Dwight L. Myers recently accepted

a post under the city engineer in Spokane, Wash., as construction engineer. His work will be wholly devoted to a $3,500,000 construction job of which about ten per cent has already been awarded to contract.

W. Clark Mason has resigned as metallurgist for the Inspiration Consolidated Copper Co. and has gone to San Francisco as metallurgist for the Merrill Co. His new address is Hill Castle Apt., 1431 Jackson St., Oakland 12, Calif.

R. K. Matheson is now reached at the Coronado Copper and Zinc Co., Bella Vista, Calif.

Donald H. McLaughlin has been appointed chairman of the National Committee of sponsors of the Harvard Foundation for Advanced Study and Research.

Herbert H. Mellus is pit engineer of the new open pit project of the Inspiration Consolidated Copper Co., Inspiration, Ariz.

James J. Merle has changed his address to the Fairview Collieries Corp., Box 86, Danville, Ill. He was chief chemist for the Ayrshire Patoka Collieries Corp.

Henning C. L. Meyer, who used to be with the New Jersey Zinc Co., has moved to 1507 S. 78th St., West Allis, Wis. He is working for the Allis-Chalmers Mfg. Co.

Gilbert Monroe graduated in mining engineering from the University of Alaska last May and now works as a junior engineer with an aircraft company. His address is Apt. 12, Darrell Hotel, 703 8th Ave., Seattle, Wash.

Perry F. Narten, after graduating from Washington University, St. Louis, Mo., went to work for the U. S. Geological Survey, Washington 25, D. C.

M. J. O'Shaughnessy has become project superintendent of Allard Lake (Quebec) Mines Ltd., Havre St. Pierre, P. Q. He was with the Alger Gold Mines.

W. P. Putnam has retired from active business and is spending his winters at 1001 Hamlin Ave., Orlando, Fla., where he is enjoying a change from northern winters.

Edwin H. Oshier is field superintendent for the Round Mountain Gold Dredging Corp., Round Mountain, Nev. He had been with the Golden Queen Mining Co., Mojave, Calif.

W. C. Page became assistant general manager of Western operations of the U. S. Smelting Refining and Mining Co. on March 1. In addition to his general duties, Mr. Page will continue to have direct supervision over the Midvale plant operations and the refining operations of the Company.

K. Peters

K. Peters, formerly manager in charge of the mining and metallurgical operations of the Mahad Dahab property of the Saudi Arabian Mining Syndicate, has been appointed consultant on mining affairs to the Kingdom of Saudi Arabia. Mr. Peters will make his headquarters in Jedda, Saudi Arabia.

Louis A. Panek is associated with the Bureau of Mines at College Park, Md., doing research in connection with roof control and the use of suspension supports. He is visiting properties where suspension supports are being introduced in order to keep informed of the problems being encountered in the field.

Everett M. Paris is employed as mine superintendent with the U. S. Vanadium Corp. at Uravan, Colo.

Roy I. Petersen is assistant superintendent of the shaft sinking division of the Bethlehem Collieries Corp., and is addressed at R. D. 1, Bentleyville, Pa.

Alan P. Ploesser has gone to Baguio, Philippine Islands, to work for the Benguet Consolidated Mining Co.

O. Edward Pothier is a mining engineer in the exploration department of the Simplot Fertilizer Co., Pocatello, Idaho. He receives mail at Rt. 7, Boise, Idaho.

Emmett S. Pugh, president of the Raleigh Smokeless Coal Co. until 1946 when it was sold to the Blackstone Coal Co., has announced the organization on Feb. 1 of a new operating sales company called the Raven Pocahontas Co. The new company will be owned entirely by the producing companies represented, the officers, and the employes. The four operating companies concerned at present are Raven Coals, Inc., the Raven Peerless Co., Raven Red Ash Coal Co., and an affiliate, and the Red Ash Mining Co., which are producing about 2500 tons per day of mid-volatile coal.

Richard Quirk has been appointed assistant superintendent of the Morococha department of the Cerro de Pasco Copper Corp., Morococha, Peru. He was formerly general mine foreman there.

Alfred L. Ransome has been transferred from his former post as supervising engineer of the San Francisco office of the metal economics branch of the Bureau of Mines to one of similar capacity with the newly established metal economics branch office in Juneau, Alaska. On Dec. 5, a little "sourdough," David Miles, 7 lb. 4 oz., was added to the Ransome family roster by way of St. Anns Hospital, Juneau.

Avery H. Reed, Jr., is employed as a mining engineer with the Bureau of Mines, Box L, University, Ala. He had been general superintendent of the Gilbert & Hageman Co., Lexington, Ky.

Gilbert R. Richardson has gone "down under" to Sydney, N. S. W., where he is reached at the Eveready (Australia) Pty. Ltd., P. O. Box 37, Mascot.

A. E. Roberts, since he was graduated from the College of Mines at the University of Arizona last May, has been employed on the engineering staff of the Magma Copper Co. at Superior, Ariz.

Ernest H. Rose, now doing research and development work for the Tennessee Coal, Iron and Railroad Co., has been appointed to the Committee on Raw Materials of the Atomic Energy Commission. Mr. Rose, whose work with TCI is directed toward the exploitation of Alabama's silicious iron ores, was mill superintendent for the International Nickel Co. of Canada at Copper Ciff, Ont., for many years.

Clyde R. Russell, who was mine superintendent of the Tonopah Belmont Consolidated Mining Co., Tonopah, Nev., has gone to Oruro, Bolivia, where he is addressed at Casilla No. 154.

Margaret A. Ryan went to work for the Anaconda Copper Mining Co. in January as a technical chemist at the Washoe smelter, Anaconda, Mont.

V. P. Sokoloff is a soil scientist and geochemist in the geochemical prospecting unit of the U. S. Geological Survey, Denver Federal Center, Denver 14, Colo.

Alex E. Stutter, secretary of the Committee on Membership, AIME, and his wife Frances, are the proud parents

of George Alexander who was born March 18 at the Bethany Deaconess Hospital, Brooklyn, N. Y.

Robert A. Stauffer has been elected vice-president and director of research of the National Research Corp., Cambridge, Mass. Mr. Stauffer, a Harvard graduate, has been associated with the company since 1942.

J. S. Sumner is engaged at present in geophysical prospecting on the Marquette range. He is addressed in care of the geological department of the Cleveland-Cliffs Iron Co., Ishpeming, Mich.

Charles Will Wright has been acting as consulting engineer for ECA on a part-time basis, but his permanent connection continues as consultant to Westinghouse Electric International, Rm. 1810, 40 Wall St., New York City. He spends a part of each week in Washington, where his home address is 2540 Massachusetts Ave., Washington 8, D. C.

William E. Wright has changed his professional address from Pennsylvania State College to commodity specialist, U. S. Tariff Commission, Washington 25, D. C.

George G. Yeager, with the Aluminum Co. of America, has been transferred to the company's purchasing department in Pittsburgh. His address is 3229 Circle Drive, Pittsburgh 27, Pa.

• In the Metals Divisions

Elbert E. Alpers works for the General Motors Corp. central foundry division as a metallurgist. Mail reaches him at Apt. 2, 1201½ E. Main St., Danville, Ill.

J. R. Brady has been made supervisor of the research and testing department of the Wisconsin Steel Works, Chicago.

M. H. Caron, of Delft, and **Herman Ebbinge,** of Den Haag, Netherlands, have recently been in the United States and Canada on professional work. Professor Caron reports that the university at Delft is in serious need of a copy of AIME Transactions volume 121, on lead and zinc, now out of print. If a member has a copy he can spare, he would like to be advised.

E. Corbin Chapman has been appointed chief metallurgist of Combustion Engineering-Superheater, Inc., and will continue to make his headquarters in Chattanooga, Tenn. Mr. Chapman has been employed by Combustion since his graduation from Cornell in 1928 and is the author of numerous articles and papers on welding and metallurgical subjects. During the second World War he served as supervisor of the National Defense Research Council project on development of electrodes for welding armor plate.

Herbert J. Cooper is working for the Cooper Alloy Foundry Co. as an engineer on research and development. He lives at 336 Harding Dr., South Orange, N. J.

Otto Barth

Otto Barth on Feb. 25 was named professor of nonferrous metallurgy at the Royal Institute of Technology in Stockholm.

Lee H. DeWald is metallurgical engineer for the National Cylinder Gas Co., manufacturers of industrial gases and welding equipment, Chicago. He receives mail at 828 Main St., Aurora, Ill.

Delmar W. Dow has the job of metallurgical engineer with the Permanente Metals Corp. at the Mead works, Spokane, Wash. His address in Spokane is 10014 Whittier St., Rt. 7.

Norman F. Dufty is now employed as technical assistant in the open hearth department of the Australian Iron and Steel Co., G.P.O. Wollongong, N. S. W. Australia.

Clarence W. Fabel is no longer employed by Remington Rand, Inc.; his present post is metallurgist with the Simonds Saw and Steel Co., Lockport, N. Y.

John H. Fuqua graduated from the Missouri School of Mines in January and has taken a job with the American Steel Foundries in the research laboratory at their Indiana Harbor plant. His address is 8020 S. Paulina St., Chicago.

William K. Heid is taking the supervisory training program at the Pontiac motor division of the General Motors Corp. He lives at 89 S. Roselawn Drive, Pontiac 20, Mich.

K. H. Heino is working at Noranda, Que., as technical assistant for Noranda Mines Ltd.

George O. Hiers works in the research laboratories of the National Lead Co., 105 York St., Brooklyn 1, N. Y.

G. W. Higgins works for the Wehr Steel Co. at West Allis, Wis. His mail goes to 1743 S. 58th St., West Allis.

Erle J. Hubbard has resigned from his post as foundry superintendent in the piston ring division of the Koppers Co. and accepted the post of foundry manager of the Janney Cylinder Co., 7421 State Rd., Philadelphia, Pa.

Raymond A. Humphreys is metallurgical inspector and secretary of the materials review board of the Chase Aircraft Co., West Trenton, N. J.

William A. Johnson, formerly at Oak Ridge, Tenn., at the Clinton laboratory of the Monsanto Chemical Co., has gone to Pittsburgh, Pa., to work with the atomic power division of the Westinghouse Electric Corp.

F. G. Kerry, who lives at 227 Glendale Rd., Scarsdale, N. Y., is manager of the engineering development department of Spaco Inc. (Air Liquide), oxygen producers and plant manufacturers, 529 Chrysler Bldg., New York City 17.

Charles H. T. Wilkins

Charles H. T. Wilkins, formerly metallurgist with the Copperweld Steel Co., heads the National-Standard Company's industrial fellowship at Mellon Institute in Pittsburgh. The Niles, Mich., company established the fellowship to investigate, in a long-range program, major problems related to the technology of fine wire products, such as tire bead wire, strand for heavy duty tire casings, music wire, and aircraft and textile wires. Also to be studied are problems related to flat strip for use in such products as piston rings, razor

blades, clock and watch springs, pen points, and umbrella ribs. Mr. Wilkins was graduated from VMI and subsequently pursued advanced work in metallurgy at the University of Pittsburgh, receiving his M.S. degree there in 1946.

C. H. Lenhart has resigned as general superintendent of the steel plant of the Iron and Steel Division of the Kaiser Co., Fontana, Calif., and is replaced by **George B. McMeans.**

Arthur M. Monson has resigned from the Stearns-Roger Mfg. Co. to enter the realty business as salesman for Foster & Barnard, Inc., Chamber of Commerce Bldg., Denver.

William R. Opie

William R. Opie, a research assistant in metallurgy at MIT, received a degree of Doctor of Science in metallurgy in February. He is now employed as a research metallurgist by the American Smelting and Refining Co. in their central research department at Barber, N. J. His home address is 99 3rd St., Raritan Township, Fords, N. J.

• In Petroleum Circles

Paul T. Bail is working for the Bureau of Mines at Franklin, Pa. He used to be with the Stanolind Oil and Gas Co. in Wink, Texas.

Robert E. Bennett has joined the staff of the California Co. as a petroleum engineer at Harvey, La.

Paul Biggs resigned his job with the Stanolind Oil and Gas Co. at Big Lake, Texas, in February and is now employed by the Bureau of Mines at the petroleum and oil shale experiment station, Laramie, Wyo., as a petroleum engineer.

Guy Borden, Jr., assistant professor of petroleum engineering at Louisiana State University, has joined the production research department of the Stanolind Oil and Gas Co. at Tulsa, Okla.

Pete W. Cawthon, Jr., is completing a training program in the production department of the Phillips Petroleum Co. He finished work on a master of engineering degree, petroleum, at the University of Oklahoma last September. His degree will be granted in June.

Courtney E. Cleveland, after spending a number of years as geologist and exploration engineer with Bralorne Mines Ltd. of Vancouver, B. C., is now joining the geological staff of the Barnsdale Oil Co., 735 8th Ave. W., Calgary, Alta.

Robert R. Cocke, III, is a student at the University of Texas as well as part time engineer for the Railroad Commission of Texas. He lives in Apt. 1, 1807 Brazos, Austin, Texas.

Lynn R. Cook, Jr., can be reached at the Richmond Exploration Co., Apartado 93, Maracaibo, Venezuela.

William R. Corby is working for the Spartan Drilling Co. in the Golden Meadow field. At present he is doing work in both the production and drilling departments. His address is Box 506, Golden Meadow, La.

William J. Cox, as a petroleum geologist with the Creole Petroleum Corp., has gone to Barcelona, Anzoategui, Venezuela.

Jeral J. Crowder resigned as petroleum engineer from the Gulf Oil Corp. the first of the year to assume duties with the Quintana Petroleum Corp. as petroleum engineer for their producing and drilling department at Houston, Texas. Mr. Crowder attended Texas A&M College, studying petroleum engineering, and later he received a B.S. degree in mechanical engineering from the University of Houston.

Charles E. Davis, upon graduation from SMU in Dallas last May with a B. S. in geology, accepted a post with the Gulf Oil Corp. and was subsequently assigned to work in the N. Ward-Estes field of Ward and Winkler Counties, Texas, as a field geologist.

John O. Davis graduated from the University of Texas with a degree in petroleum engineering in February 1948 and since that time has been employed by the Jergins Oil Co. at Victoria, Texas, as production foreman.

Jack M. Denson graduated from the University of Texas last June with a B. S. degree in petroleum engineering and is now working for The Texas Co. as a petroleum engineer trainee. His address is Box 82, Buckeye, N. Mex.

William C. Dinger, formerly with the Houston Oil Co. of Texas, can be reached at Rock Springs, Wyo., where he is associated with the Mountain Fuel Supply Co.

John R. Evans is undergoing a one year training program as junior petroleum engineer for the Creole Petroleum Co., New York City, but receives mail in care of R. N. Dyer, Humble Oil and Refining Co., Houston, Texas.

Gearld I. Freeze, former instructor in the department of petroleum engineering at the University of Kansas, is now in the production department of the Phillips Petroleum Co., Box 1605, Hobbs, N. Mex.

Ionel I. Gardescu has been promoted to manager of the gas reserve department of the Transcontinental Gas Pipe Line Corp., Oil and Gas Bldg., Houston 2, Texas.

John T. Gary, with the Continental Oil Co., was transferred on Jan. 1 from district petroleum engineer at Wichita Falls, Texas, to production engineer in the general office at Ponca City, Okla.

Benjamin F. Hake can be reached at the geological department of the Gulf Oil Corp., Box 1166, Pittsburgh 30, Pa.

A. S. Hawley resigned in January from the Schlumberger Well Surveying Corp. and accepted the post of geologist with the Union Oil Co. in Bakersfield.

Jack P. Hays is production superintendent for the Intex Oil Co., Dallas, Texas, but his mail goes to 64 Bacon Bldg., Abilene, Texas.

Richard V. Hughes, formerly with the Penn Grade Crude Oil Assoc., has gone to Stanford, Calif., as geologist with the Stanford Research Institute.

Joe B. Justus graduated from Louisiana State and is working for the California Co., Ruston, La., as a production engineer.

James E. Keller has gone to Caracas, Venezuela, to work for the Creole Petroleum Corp. He is addressed there at Apartado 889.

Leslie A. Leuzinger is field engineer at Rangely, Colo., for the Union Pacific Railroad Co., oil development.

Robert L. Lindauer, Jr., receives mail at P. O. Box 357, Katy, Texas. He is a junior gas engineer with the Humble Oil and Refining Co.

Donald P. McCarthy, who was a student at the Montana School of Mines, is working in the gological department of the Sinclair Prairie Oil Co., Albuquerque, N. Mex.

John M. McLain is junior exploita-

tion engineer with the Shell Oil Co., Houston, Texas, but gets his mail at 823 Main St., Hattiesburg, Miss.

Richard H. Zinszer can now be reached in care of the research department of the Union Oil Co. of California, Wilmington, Calif.

Obituaries

Charles E. LeNeve Arnold

AN APPRECIATION BY JAMES L. HEAD

"Charlie Arnold died yesterday." Seldom does such sad news spread as rapidly as it did on Monday morning, Jan. 24, throughout the six floors of 25 Broadway, New York City, which house the vast New York organization of Anaconda. From top brass to office boy, from veteran to newest comer, all felt a distinct and unusual personal loss for he enjoyed the widest personal acquaintanceship in the entire organization. When the news of his passing was communicated to Inspiration, Potrerillos, Chuquicamata and Cananea, to each of which he had made definite contribution, to the Mining Club and to Institute Headquarters, it evoked the same reaction and added additional evidence of the particular esteem in which he was held by everyone who knew him. He was always the considerate, discerning, courteous, gentlemanly and unfailing friend of all. It is to such rare individuals that great organizations really owe that intangible thing, esprit de corps.

"None knew thee but to love thee,
Nor named thee but to praise"

For the record, Charles Everard LeNeve Arnold was born in Auckland, New Zealand, on Sept. 13, 1883, where he is survived by a father and brother. He attended Auckland University from March to November, 1901. His choice of a career in the mineral industry must have been an early one, for between 1900 and 1902 he was a bullion melter and assayer at Waihi, New Zealand. I do not know why he came to the States, but he did so in 1902, matriculating at the University of California, from which he was graduated in 1906. Here he was a schoolmate of Erle V. Daveler, James S. Wroth, John Tyssowski, and the late Spencer Browne. One of his favorite tales—and he was a raconteur par excellence—was of his first day in this country when he was initiated into American barbershop practice—and paid for the "works."

His summer vacations during college followed the traditional pattern of the embryo mining engineer of that day. We have such unglamorous items as machine hand, Union Iron Works, San Francisco; miner, Keystone Gold Mine, Amador City, Calif.; cyanide hand, North Star Corp., Grass Valley; sampler, Fresno Copper Corp., Gordon, Calif.; and draftsman at Ely for Nevada Consolidated. Following graduation, he was from 1905 to 1911 construction and mine engineer for the Girous Consolidated Mines Co. at Kimberley, Nev., and I think it was here that he met the future Mrs. Arnold, Miss Genevieve Mills.

Moving on to Inspiration, the newest addition to the porphyry copper group, he was mine engineer there from 1911 to

1918 and had much to do with the sound planning which was the basis for the success of that operation. In 1918, he was called to New York City and it is not surprising that with this background and wealth of experience he was designated to function in a similar capacity in the planning and development of Anaconda's newest venture, the great Andes Copper Mining Company's mine at Potrerillos, Chile. In 1924 he became assistant to William Wraith, vice-president, Andes Copper Mining Co., Greene Cananea Copper Co., and Inspiration Consolidated Copper Co., and he served in this capacity until Mr. Wraith's retirement at the end of 1945. Subsequently he continued in close touch with the operations of these companies.

All of which adds up to the fact that Arnold was an exceedingly capable engineer. So useful, dependable, and conscientious was he in the ever essential "information please" capacity, that he was never quite able to shake off the shackles and inhibitions which so often prevent a fine engineer from achieving top executive rank.

He became a member of AIME in 1906 and was one of headquarters' dependables. He was particularly active in the New York Section, having served as secretary, 1934, treasurer 1935-37, vice-chairman, 1938 and chairman 1939. Always intimately connected with the Annual Meetings of the Institute in New York City, his designation as chairman of any committee, annual banquet, informal dance, reception, etc., insured the success of that particular function. He had looked forward to attending the recent Annual Meeting in San Francisco. At the time of the organization of the Mining Club in New York City in 1930, he was invited to become a charter member and he was elected to membership in the Mining and Metallurgical Society of America in 1939.

The fact that he had suffered an initial heart attack on Labor Day, 1940, did not deter him from carrying on, and although he was possibly living on borrowed time, he continued to be the genial and unforgettable Charlie Arnold.

D. B. McAllister

All who have regularly attended the Annual and Regional meetings of the Institute will be saddened to hear of the death of one of those whose presence has contributed so much to those occasions—D. B. McAllister, of San Luis Potosi, Mexico. "Mac," as he was known to so many friends, and to his wife as well, died on March 28. The last time we saw him was at the stag dinner at the San Francisco meeting, when we sat next to him. At that time he seemed a bit repressed for Mac, but we had no idea this might have been a foreboding. We had exchanged pleasantries at many other meetings, and he was always making a joke of something, or assuming a character that he thought might shock strangers. We are sure that a host of Institute members must have had a cordial invitation to visit at the McAllister home in San Luis Potosi, as we have, and no doubt many have been able to drop off there, as we have not. His good wife was always with him at meetings, endeavoring to keep him straight, as he explained. She will be an especially lonely woman. The Institute has lost not only a competent engineer but an active member and one who, although not on many of its technical programs as an author, helped greatly to make attendance at its meeting a satisfying experience.—*E. H. R.*

Daniel Bruno McAllister (Member 1920), was a native Bostonian, born in 1881, and a Harvard graduate, class of 1905. The year after graduation, he worked as a surveyor for the Pennsylvania tunnels in New York City, and for the next three years held engineering positions in West Virginia, Michigan and New York. In 1910 he became an engineer for the Cia. Metalurgical Mexicana, beginning a lifelong association with Mexican mining which was interrupted only by four years in New Mexico and two years with New York State's Public Service Commission. In 1925 he leased the El Barreno mine in San Luis Potosi, and for the past twenty-three years had resided in that city, actively engaged in mining enterprises.

Necrology

Date Elected	*Name*	*Date of Death*
1939	LeGrande D. Barrett	Unknown
1920	Lucius A. Butler	Jan. 23, 1949
1946	Herschel E. Denton	March 30, 1949
1931	Cecil Drake	Jan. 31, 1949
1917	Frederic W. James	Dec. 28, 1948
1920	Daniel B. McAllister	March 28, 1949
1915	Alexander G. McGregor	March 4, 1949
1936	Arthur S. Nichols	Feb. 18, 1949
1916	Chase S. Osborn	April 11, 1949
1948	Thomas M. Robertson	Aug. 16, 1948
1940	William A. Rose	Jan. 30, 1949
1904	David R. Thomas	March 4, 1949

HAROLD E. WILLSON (Member 1916), West Virginia mining engineer who headed his own firm at Oak Hill, is dead. A graduate of the University of Illinois, class of 1916, Mr. Willson worked with various West Virginia coal companies before forming his own engineering organization, the H. E. Willson Engineering Co., in 1918, which he operated until the time of his death.

Proposed for Membership

Total AIME membership on March 31, 1949, was 15,363; in addition 4082 Student Associates were enrolled.

ADMISSIONS COMMITTEE

James L. Head, Chairman; Albert J. Phillips, Vice-Chairman; George B. Corless, T. B. Counselman, Ivan A. Given, George C. Heikes, Richard D. Mollison, and Philip D. Wilson.

Institute members are urged to review this list as soon as the issue is received and immediately to wire the Secretary's office, night message collect, if objection is offered to the admission of any applicant. Details of the objection should follow by air mail. The Institute desires to extend its privileges to every person to whom it can be of service but does not desire to admit persons unless they are qualified.

In the following list C/S means change of status: R, reinstatement; M, Member; J, Junior Member; AM, Associate Member; S, Student Associate; F, Junior Foreign Affiliate.

ALABAMA

Bessemer — SAUNDERS, ARCHIE OLIVER. (AM). Service engineer, Independent Pneumatic Tool Co.

Florence—SHERWIN, RALPH SIDNEY. (R—M). Vice-president in charge of alumina development, Reynolds Metals Co.

ARIZONA

Hayden—TUCK, FRANK JOSEPH. (R—M). Mill superintendent, Kennecott Copper Corp.

Jerome—FULTON, DAVID HOLMES. (C/S—S-J). Stope engineer, Phelps Dodge Corp.

Superior — ANDERSON, RICHARD COLEMAN. (C/S—J-M). Mining engineer, Magma Copper Co. ROBERTS, ALVAN E., JR. (C/S—S-J). Transitman; engineering dept., Magma Copper Co.

ARKANSAS

El Dorado — McDONALD, PAUL CRANFORD. (R,C/S—J-M). Field superintendent, C. H. Murphy & Co.

Little Rock—HESS, ALBERT JOHN. (M). Mining engineer, The Milwhite Co.

CALIFORNIA

Alhambra—NASH, WILLIAM FRANCIS, JR. (M). Staff consultant, C. F. Braun & Co.

Berkeley—PIETROKOWSKY, PAUL. (C/S—S-J). Research metallurgist, University of California. SCHUELER, DORNER TURNER, JR. (C/S—S-J). Chief engineer, Industrial Minerals & Chemical Co.

Buena Park—WRIGHT, CHARLES CATHBERT. (J). Chemist, Oil Well Research, Inc.

Inglewood—GRAVES, DOYLE THEODORE. (J). Subsurface engineer, Union Oil Co. of California.

Long Beach—VAN RIPER, JOHN. (M). Petroleum engineer, Continental Oil Co.

Los Angeles—BOYES, RALPH LEE. (J). Assistant field engineer, Union Oil Co. EVANS, THOMAS O. (M). Mining engineer, Atchison, Topeka & Santa Fe Railway Co. JAKOSKY, JOHN JAY, JR. (C/S—S-J). Engineer, International Geophysics, Inc. MARSHALL, IRA ALLISON, JR. (J). Production equipment engineer, Shell Oil Co.

Ojai — DOIG, KEITH. (J). Junior mechanical engineer, Shell Oil Co.

San Francisco — MORBIO, CARLO SUTRO. (AM). Consultant.

South Gate — LIETZOW, CLYDE HARVEY. (J). Sales engineer, Pelton Water Wheel Co.

South Pasadena—PAUL, WILLIAM GLAE, JR. (J). Representative, Kobe, Inc.

Ventura—WEST, W. FRANK. (C/S—S-J). Petroleum engineer-trainee, Continental Oil Co.

Whittier—FAULL, RICHARD FRANCIS. (M). Manager, La Habra Laboratory, California Research Corp.

Wilmington—FEI, ROBERT FLEMING. (C/S—S-J). Petroleum engineer-trainee, Union Oil Co.

COLORADO

Denver—BOARD, VIRGIL LEE. (M). President, Western Exploration & Management Co. SNEDDEN, HENRY DAVID. (R,C/S—J-M). Metallurgist, Humphreys Investment Co.

Golden — LOEB, MICHEL JEAN. (C/S—S-J). Graduate student, Colorado School of Mines.

Trinidad—DUREN, JACK DANIEL. (C/S—S-J). Junior exploitation engineer, Shell Oil Co.

CONNECTICUT

Manchester—DAY, ROBERT B. (C/S—S-J). Metallurgical engineer, Linde Air Products Co.

New Haven—HIBBARD, WALTER ROLLO, JR. (C/S—J-M). Assistant professor of metallurgy, Yale University.

Ridgefield — MARTIN, MAURICE HENRI. (M). Chief engineer, Schlumberger Well Surveying Corp.

Stratford — CLARK, HOWARD T., JR. (M). Research metallurgist, Remington Arms Co.

Waterbury — DUBPERNELL, GEORGE. (M). Manager, Waterbury laboratories, United Chromium.

DISTRICT OF COLUMBIA

Washington—WARNCKE, RUSSELL GEHRING. (R,C/S—JA-M). Mining engineer, safety branch, Bureau of Mines. WRIGHT, WILLIAM EDWARD. (C/S—S-J). Commodity specialist (ceramics), U. S. Tariff Commission.

GEORGIA

Marietta—WILLINGHAM, CHARLES BERRIEN. (M). Sales engineer, Joy Mfg. Co.

IDAHO

Kellogg — McDONALD, JAMES THOMAS. (C/S—S-J). Surveyor, Bunker Hill & Sullivan Mining & Concentrating Co.

Wallace — NELSON, VERNON JEROME. (AM). Division manager, Coeur d'Alene mining division, Washington Water Power Co.

ILLINOIS

Chicago — DICKTER, IRVING A. (M). Plant metallurgist and chemist, Goodman Mfg. Co. DYER, HARRY BISHOP. (R,C/S—S-J). Research metallurgist, Republic Steel Corp. LEWY, JAMES KAY. (J). Metallurgical trainee, Inland Steel Co. SILVERSTEIN MITCHELL. (C/S—S-J). Metallurgist, Silverstein & Pinsof.

Marshall — NAERT, GILBERT ALPHONSE. (J). Petroleum engineer, Ohio Oil Co.

Mt. Vernon—SHICK, ROBERT L. (R,C/S—S-M). District petroleum engineer, Sohio Petroleum Co.

Olney — STORSETH, BILLY JOE. (J). Sales engineer, Lane-Wells Co.

INDIANA

Evansville—VAUGHAN, JERRY R., JR. (R,C/S—S-M). Petroleum engineer, Sun Oil Co.

West Lafayette—GUARD, RAY W. (C/S—S-J). Instructor, metallurgical engineering, Purdue University.

KANSAS

Eureka—McGINNIS, WARD ALLYN. (M). President and general manager, Ring-Mac Oil Co.

Madison—JONES, FRANK T. (J). Junior engineer, Cities Service Oil Co.

Manhattan — WIKLE, KEITH GORDON. (R,C/S—S-J). Professor of engineering metallurgy, Kansas State College.

Wichita — HARWOOD, WARREN KENNETH. (R,C/S—S-J). Secretary-treasurer, Harwood Oil Co.

KENTUCKY

Wheelwright—ANDERSON, ROBERT BRADFORD. (C/S—S-J). Engineer, Inland Steel Co.

LOUISIANA

Baton Rouge—PYBURN, THOMAS DENNIS. (C/S—S-J). Service engineer, Baroid Sales Div., National Lead Co.

New Orleans—WATSON, MARTIN C. (M). Assistant area manager, Southeastern area, Schlumberger Well Surveying Corp.

Shreveport—LOGAN, GEORGE LYONS. (C/S—S-M). Chief petroleum engineer, Lyons & Prentiss.

MARYLAND

Berwyn Heights — BROWNING, JAMES SCOTT. (C/S—S-J). Metallurgist, Bureau of Mines.

MASSACHUSETTS

Lexington — HURLEY, PATRICK MASON. (C/S—J-M). Assistant professor, MIT.

Pittsfield — GARDNER, FRANK STREETER. (C/S—J-M). Metallurgist, General Electric Co.

Springfield—NAST, PAUL H. (M). Mining drill sales supervisor, Worthington Pump & Machinery Corp.

MICHIGAN

Detroit—SCHMIDT, WILLIAM ATKINSON. (C/S—S-J). Graduate trainee, Cadillac Motor Car Div., General Motors Corp.

MISSISSIPPI

Clinton — MATHER, KATHARINE KNISKERN. (C/S—J-M). Head, petrography section, concrete research div., Waterways Experiment Station.

Hattiesburg — McLAIN, JOHN McAFEE. (C/S—S-J). Junior exploitation engineer, Shell Oil Co.

West Jackson—JEFFREYS, GEOFFREY. (R-M). Consultant, petroleum geology.

MISSOURI

Herculaneum — MICKLE, RALPH GLOVER, JR. (R,C/S—S-J). Metallurgist, St. Joseph Lead Co.

St. Louis—VOGT, JOSEPH CHARLES. (C/S—S-J). Department head, Laclede Gas-Light Co. SCHRAUT, JOSEPH ANTHONY, JR. (C/S—S-J). Geologist, concrete laboratory, Aggregate Investigation, U. S. Army Engineers.

Webster Groves—CHUBB, WALSTON. (C/S—S-J). Ludlow Saylor research fellow, Missouri School of Mines & Metallurgy.

MONTANA

East Helena—MORAN, FRANK C. (M). Assistant superintendent, East Helena plant, American Smelting & Refining Co.

NEW JERSEY

Riverside — TURSI, PETER BUDD. (M). Metallurgist, Riverside Metal Co.

South Orange—COOPER, HERBERT JAY. (C/S—S-J). Engineer of research & development, Cooper Alloy Foundry Co.

NEW YORK

Brooklyn — DORKOVICH, VICTOR. (R-M). Senior member, R. S. Aries & Associates. KANE, NATHAN MILTON. (R,C/S—S-J). Piping engineer, Lummos Co.

Mt. Vernon — DONELLON, JOHN BERNARD. (M). Process control chemical engineer, Callite-Tungsten Corp.

Natural Bridge—BLAZOVIC, PHIL, JR. (C/S—J-M). Plant metallurgist, Wheeling Steel Corp.

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Niagara Falls—DEMMON, NEWTON KEITH. (M). Service engineer, National Carbon Co.

Schenectady—CECH, ROBERT EDWARD. (C/S—S-J). Research assistant, physical metallurgy section, General Electric research laboratory. MARTIN, DONALD LUTHER. (C/S—J-M). Research metallurgist, General Electric Co.

Sherrill — MOULTON, WALTER EVERSON. (M). Chief metallurgist, Oneida, Ltd.

Upton — TEITEL, ROBERT JERRELL. (C/S—S-J). Associate metallurgist, Brookhaven National Laboratories.

OHIO

Cleveland — HAMJIAN, HARRY JOHN. (J). Aeronautical research scientist, National Advisory Committee for Aeronautics.

Columbus — BRISON, ROBERT JOSHUA. (R,C/S—S-J). Research engineer, Battelle Memorial Institute. SCHIPPEREIT, GEORGE HENRY. (C/S—S-J). Research engineer, Battelle Memorial Institute.

Middletown — ROTHE, LEONARD WILLIAM. (C/S—S-J). Metallurgical trainee, Armco Steel Corp.

OKLAHOMA

Konawa — QUILLIN, JOHN PAUL. (C/S—S-J). Trainee engineer, Standard Oil of Ohio.

Tulsa—HALEY, KENNETH WENDELL. (M). Chief petroleum engineer, Deep Rock Oil Corp. HUZAREVICH, JULIAN ELI. (C/S—S-J). Junior petroleum engineer, Stanolind Oil & Gas Co. PERRY, RALPH. (M). Director, Core laboratory, Gulf Oil Corp. WILSON, SAM A. (M). Chief engineer, Maloney-Crawford Tank and Mfg. Co.

PENNSYLVANIA

California — HESS, WILLIAM EDWARD. (M). General superintendent, Vesta Shannopin coal division, Jones & Laughlin Steel Corp.

Commodore—SIMPSON, JOHN FAIRFULL, JR. (C/S—S-J). Junior mining engineer, Clearfield Bituminous Coal Corp.

Frackville — ROSELLA, JOHN JERRY. (M). Mining engineer, Bureau of Mines.

Palmerton—RAMSEY, PAUL WILLARD. (C/S—J-M). Metallurgist, development engineering division, New Jersey Zinc Co. (of Pa.).

Philadelphia—MULDAWER, LEONARD. (J). Assistant professor of physics, Temple University.

Pittsburgh — ELKIN, JAMES ELWELL. (M). General superintendent, Coal department, Duquesne Light Co. HENSCHEN, ARTHUR EVANS. (C/S—S-J). Sales engineer, Aluminum Co. of America. VOELKER, HENRY RONALD. (C/S—S-J). Student-graduate, doing nondegree studies at the University of Pittsburgh.

State College — NIELSEN, RALPH FREDERICK. (M). Assistant professor of petroleum and natural gas engineering, Penn. State College. SCHANZ, JOHN J., JR. (C/S—S-J). Instructor, mineral economics, Penn. State College.

Summit Hill—KUEBLER, CHARLES SWANK. (R,C/S—J-M). District superintendent, Lehigh Navigation Coal Co.

SOUTH DAKOTA

Vermillion—ROTHROCK, E. P. (M). State geologist, South Dakota Geological Survey.

TEXAS

Arp—ROGERS, WILLIAM JEROME. (R,C/S—S-M). District engineer, Sinclair Prairie Oil Co.

Austin—McKETTA, JOHN J., JR. (M). Associate professor of chemical engineering, Univ. of Texas.

Beeville — McDOWELL, OLIVER GEORGE. (J). District engineer, Houston Oil Co. of Texas.

Dallas—BRANSON, UZZELL S., JR. (M). Reservoir analyst, James A. Lewis Engineering. CHAMBERS, ELLEN ADELE. (J). Junior chemist, Atlantic Refining Co. LORING, WILLIAM THOMAS. (C/S—J-M). Petroleum engineer, Core Laboratories, Inc. MARSHALL, DAN LANDRY. (C/S—J-M). Geological and petroleum engineer, DeGolyer & MacNaughton.

El Paso—BARSA, DAVID J. (J). Fire assayer, Phelps Dodge Refining Corp. HERPERS, FRANK MANUEL. (M). Assistant general foreman, casting department, Phelps Dodge Refining Corp. LAUREL, LOUIS PHILLIP. (AM). Manager, machinery department, Mine & Smelter Supply Co. McNAMARA, FRANCIS ROBERT. (M). District manager, Gardner Denver Co. RINDOM, VIRGIL JENNINGS. (M). Chemist, Phelps Dodge Refining Co.

Fort Worth — FORBES, HENRY FRASER. (R,C/S—J-M). Region petroleum engineer, Continental Oil Co. WILSON, JOHN HUMAN, II. (C/S—S-J). Pumper, Fred H. Manning, Inc.

Houston—AUSTIN, JESS WILLIAM. (C/S—S-J). Junior petroleum engineer, Stanolind Oil & Gas Co. DUPONT, HARRY ALVIN. (R,C/S—S-J). Petroleum engineer, Phillips Petroleum Co. GETZENDANER, AVELETTE EDMOND. (M). Zone geologist, Gulf Products Division, Gulf Oil Corp. LLOYD, JOHN MORGAN, JR. (J). Petroleum engineer, Stanolind Oil & Gas Co. RIDLEY, ROBERT P. (R,C/S—S-M). Reservoir engineer, The Texas Co. WAECHTER, JACK WILLIAM. (C/S—S-M). Petroleum production engineer, California Co. WATSON, JOSEPH PRESLEY, JR. (J). District engineer, Cities Service Oil Co.

Katy—LINDAUER, ROBERT LEE, JR. (C/S—S-J). Junior gas engineer, Humble Oil & Refining Co. SHARP, CARLE FARRELL, JR. (C/S—S-J). Junior reservoir engineer, Humble Oil & Refining Co.

Kilgore — ELSEY, HARRY NEILL. (M). District machinery sales engineer, Republic Supply Co.

Lubbock — WHITIS, EMETT D. (C/S—S-AM). Junior petroleum engineer, Stanolind Lubbock district officer, reservoir section, Stanolind Oil & Gas Co.

Midland — BANISTER, RICHARD CARL. (C/S—S-J). Geologist, Standard Oil Co. of Texas. WEAVER, BILLY RAY. (C/S—S-J). Associate engineer, Tide Water Associated Oil Co.

Odessa — SHANOR, PAUL JAMES. (C/S—S-J). Engineer, Phillips Petroleum Co. SHILCUTT, CHARLES E. (AM). District superintendent, Lane-Wells Co.

Premont—COIL, CARL LACY. (J). Junior petroleum engineer, Sun Oil Co.

UTAH

Clearfield—FUNK, ROBERT LOUIS. (R,C/S — S-M). Sales representative, Timken Roller Bearing Co.

Lark—BOYD BENTON. (R,C/S—J-M). Mine superintendent, Lark mine, U. S. Smelting Refining & Mining Co. RUBRIGHT, RICHARD DICKSON. (M). Associate geologist, U. S. Smelting Refining & Mining Co.

Midvale—FRESH, NEIL. (M). General mine foreman, U. S. Smelting Refining & Mining Co.

Price — REEVES, JOHN ALLEN. (C/S—S-J). Assistant engineer, Independent Coal & Coke Co.

Salt Lake City—MATES, ROBERT RICHARD. (C/S—S-J). Metallurgist, Bureau of Mines.

WASHINGTON

Spokane—OMELKA, LEON VLADIMIR. (C/S—S-J). Testing engineer, Permanente Metals Corp.

WEST VIRGINIA

Cedar Grove — PALLER, CARL ADOLPH. (M). Mining engineer, Warner Collieries Co.

Charleston—BRIBER, ALEX AUSTIN. (C/S—S-J). Junior engineer, Commercial Testing & Engineering Co.

Fairmont — SCHIMMEL, JOHN THRALL. (C/S—S-J). Time study engineer, Consolidation Coal Co.

Weirton — HARRIS, RALPH WILLIAM. (C/S—S-J). Tester, first class, Weirton Steel Co.

Wheeling — FLANDERS, ALBERT CHARLES. (R,C/S—S-M). Mine superintendent, Carbola Chemical Co.

ALASKA

Anchorage — McANERNEY, JOHN MARSHALL. (R,C/S—J-M). Chief geol-

ogist, Alaska district, Corps of Engineers.

Juneau — WARFIELD, ROBERT STEWART. (C/S—S-J). Assistant mining engineer, exploration and development division, Bureau of Mines.

BRITISH COLUMBIA

Victoria—LINEHAM, JOHN DONALD. (C/S—S-J). Assistant controller, petroleum and natural gas, Government of Province of British Columbia.

ONTARIO

Falconbridge — WARNER, JOHN PELHAM. (J). Graduate trainee, Falconbridge Mines, Ltd.

Missanabie—CARROLL, JAMES WILLARD. (M). Mine superintendent, Renabie Mine.

Ottawa — KOZLOWSKI, HENRY JULIAN. (R,C/S—S-J). Research metallurgist, Bureau of Mines, Ottawa.

QUEBEC

Thetford Mines—JENKINS, GEORGE FRENCH. (R,C/S—JA-M). General manager, Asbestos Corp.

NEWFOUNDLAND

Buchans — SWANSON, ERIC ALFRED. (M). Assistant geologist, Buchans Mining Co.

CUBA

Pinar del Rio—HENDERSON, JAMES GEORGE. (M). Engineer in charge, Minas de Matahambre S. A.

BOLIVIA

Camiri—ROMERO LOZA, ALFONSO. (M). Production superintendent, Yacimientos Petroliferos Fiscales Bolivianos, Camiri Oilfield.

VENEZUELA

Barcelona—COX, WILLIAM JONES. (C/S—S-J). Petroleum geologist, Creole Petroleum Corp. WICKENHAUSER, LEONARD JOHN. (M). Reservoir engineer, Mene Grande Oil Co.

BELGIUM

Montigny le Tilleul—RICHARD ROBERT VALERE. (M). Director general de Usines et Acieries Allard (Belgium).

ENGLAND

London—DOWNWARD, BRIAN SUTTON. (M). Geologist, Whitehall Securities Corp. VOCE, ERIC. (M). Chief metallurgist, Copper Development Association.

ITALY

Vado Ligure — CODA, AGOSTINO GIACOMO. (M). Manager, Vado zinc works, Soc. di Montepoui.

BELGIAN CONGO

Elisabethville — VAN VINCKEROY, VICTOR. (R-M). Assistant to consulting engineer, Union Minière du Haut Katanga.

EGYPT

Cairo — TRAFFORD, EDWARD LE MARCHANT. (M). Chief exploitation engineer and manager, Anglo-Egyptian Oilfields, Ltd., Shell "Group."

SAUDI ARABIA

Dhahran—FLITTIE, CLIFFORD GILLILAND. (C/S—S-J). Assistant geologist, Arabian American Oil Co.

INDIA

Bihar — RAVEN, JOHN MANUEL. (M). Mine agent, Indian Copper Corp.

Champion Reefs—KERNICK, JOHN EDDY, JR. (M). Assistant treatment officer, Champion Reef Gold Mines of India.

NEW SOUTH WALES

Ashfield — KING, MALCOLM GEORGE. (AM). Research engineer, Australian Blue Asbestos, Ltd.

Cobar — BEATTIE, GEORGE ANDREW. (AM). Assistant underground superintendent, New Occidental Gold Mines.

Student Associates

Elected March 16, 1949

Louis L. Bergan.....Mont. Sch. Mines
John B. Clark.....Carnegie Inst. Tech.
Henry L. Hurley.....S. Dak. Sch. Mines
Nelson Severinghaus, Jr.....Univ. Ariz.
Ernest Stewart (Rein.).....Univ. Ariz.

Elected April 20, 1949

Alfred Ainsworth, Jr.....Univ Wichita
Harold G. Alford.....Univ. Tulsa
Carlton D. Bailey, Jr..Mich. Min. & Tech.
Emmet H. Balch, Jr.....Univ. Tulsa
Laurence H. Beal.....Univ. Calif.
John T. Berry (Rein.).....Texas A&M
Christy R. Bickford, Jr....Univ. Wichita
George A. Bivens.....Univ. Mich.
Dewey A. Bjork.....Mich. Min. & Tech.
John L. Black.....Otago Univ.
Robert D. Black.....Fenn Coll.
Edwin A. Blackey, Jr.....Univ. N. H.
Carter H. Boswell.....Univ. S. Calif.
Maurice H. Brady.....Univ. Nev.
Leo R. Brammer, Jr.....Univ. Tulsa
Stanley G. Britton.....Univ. Tulsa
Robert G. Broady.....Univ. Kans.
Douglas E. Brown.....Colo. Sch. Mines
Frank L. Brown.....Univ. Tulsa
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George W. Bruce.....Univ. Wichita
Robert Bulla.....Mo. Mines & Met.
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William W. Collins...Mo. Mines & Met.
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J. W. Cunningham..Carnegie Inst. Tech.
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William J. Davies.....Wash. Univ.
Charles DeAinza.....Univ. S. Calif.
Robert W. Decker.....MIT
Earle V. Dempsey.....Univ. Nev.
Joseph G. Dempsey.....Univ. Tulsa
Willis L. Dotson.....Colo. Sch. Mines
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Robert Gray.....Univ. Tulsa
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Charles A. Gyorgak.....Fenn Coll.
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H. J. Steinbuchel, Jr...Colo. Sch. Mines
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Charles V. Thrash.....Fenn Coll.
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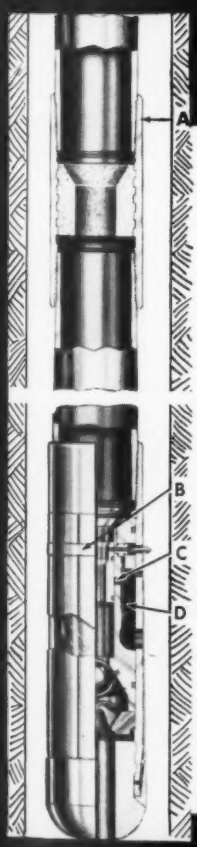

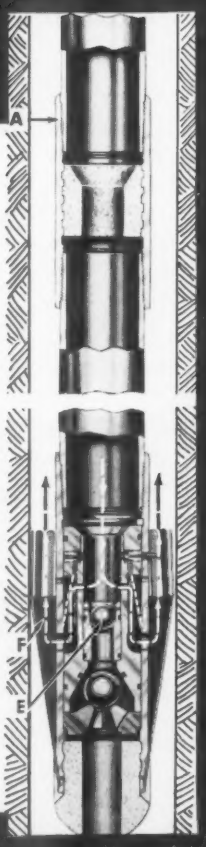

A Baker Triplex Cement Baffle Collar, installed a joint or two above the shoe, serves as a stop for the cementing plug. **B** A hold-down strap retains Baker Metal Petal Basket against the "TRIPLEX" Shoe while running-in. **C** Cementing Ports are covered by Tripping Valve until cementing is commenced. **E** After reaching the desired point in the hole, circulation is established through central passageway. A Tripping Ball is pumped down the hole to seat upon the Tripping Valve. Pressure is applied to shear the Tripping Valve shear screws and force the Tripping Valve downward to expose the cementing ports. **F** Shearing these screws also releases the Basket hold-down strap and allows the Metal Petal Basket to expand against the walls of the hole. **D** A resilient rubber, sleeve-type, back-pressure valve opens readily (see dotted white line) to permit passage of slurry into annulus above. Cementing then is carried out in conventional manner with cement slurry directed upward by the exclusive Baker "Whirling" action. Only readily drillable materials are used for all internal parts.—Look in your BAKER (or Composite) CATALOG, or write to BAKER OIL TOOLS, INC., at Houston, Los Angeles, or New York for complete information.

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THEORETICAL GENERALIZATIONS LEADING TO THE EVALUATION OF RELATIVE PERMEABILITY

WALTER ROSE, JUNIOR MEMBER AIME

GULF RESEARCH & DEVELOPMENT CO., PITTSBURGH, PENNSYLVANIA

ABSTRACT

Theoretical expressions are presented to describe wetting and non-wetting phase relative premeability relations. These expressions have then been compared with existing published data, the conformance noted being sufficiently good to satisfy the requirements of some engineering use. As a consequence, it may be supposed that relative permeability characteristics of porous media now can be inferred from basic core analysis data, in a manner more convenient (although less direct) than presently available methods of experimental evaluation.

INTRODUCTION

This paper presents a new approach to the problem of relative permeability evaluation. A classification of published discussions of relative permeability concepts which have appeared in the petroleum literature will show that previously emphasis has been placed on methods of experimental measurement, on the interpretation of the data so obtained with respect to the variable properties of the system, and on theoretical and practical considerations which relate relative permeability to gross fluid behavior in petroleum reservoirs. Essentially, no detailed examination has appeared which treats the fundamental factors controlling the quantitative features of the relative permeability relation*, although certain references can be cited[1,2,3,4,5,6,7] where a qualitative awareness of their existence and nature is indicated. This condition is explainable in terms of the recognized complexity of the problem, and in order to provide some basis for theoretical development, the general emphasis has been placed in the past on experimental procedures of evaluation, the validity of which, in principle, could be confirmed by the analysis of well and reservoir performance. However, because of the experimental difficulties which have been encountered (notably, difficulties due to the so-called "end effects"), and because of the general unreliability of field performance tests required to study the applicability of the data, relative permeability phenomena continue to be incompletely understood and described.†

In this paper is examined the possibility of predicting relative permeabilities entirely from fundamental considerations. In addition, attention is called to certain important factors, previously unemphasized in the published literature, which now can serve as a basis for the eventual experimental confirmation of this and similar theoretical approaches, as well as the experimental solution of the problem in general. Therefore, the analysis presented herein has the dual purpose both of orienting future experimental activity and also of providing an immediate solution for the relative permeability porblem, sufficiently adequate for some engineering use. It will be seen that the conclusions reached are supported by theoretical and intuitive considerations, and they are not contradicted insofar as gross features are concerned by existing concepts and interpretations of published experimental data, except as specifically noted.

Darcy's law, expressed simply as:

$$q = \frac{k}{\mu}\frac{dp}{dx} \qquad \ldots\ldots\ldots (1)$$

where q is linear rate of flow (assumed horizontal), k is the

* Intuitively, at least, we may suspect that the factors controlling the quantitative features of relative permeability relations (where relative permeability of porous media to given fluid phases is plotted as function of the saturation of these phases) will be describable in terms of basic rock texture and in terms of the character of the distribution of the immiscible fluids within the interstitial spaces. The term basic rock texture is used here to refer to the pore configurational characters dependent on factors such as grain sizes and packing as modified by cementation and other secondary processes. It will be realized that there are other factors of importance which in practical instances also will control the quantitative features of the relative permeability relation, such as those related to the various possibilities for variable interaction between the saturating fluids and the surfaces of the interstitial spaces. Thus, interstitial clays can be responsible for variable conditions of pore configuration obtaining in a given instance depending upon the nature of the saturating fluids. Variable conditions of preferential wettability also can obtain expressive of analogous possibilities in ways which will control heterogeneous fluid flow behavior. For the purposes of this paper, however, *fixed* pore configurational and wettability characters will be assumed. Moreover, no attempt will be made to establish explicitly a dependence of relative permeability on strictly fluid properties.

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References are given at end of paper.

† The poor comparison usually obtained between laboratory and field gas-oil ratios (c.f., Fig. 4 of paper by L. E. Elkins[8]) is illustrative of conditions which discourage unqualified acceptance of the results of previous studies except as presently useful approximations. In this connection, Evinger and Muskat[9] have discussed in detail the discrepancy observed between field well productivity values and values obtained from the analysis of laboratory flow data.

permeability constant, μ is fluid viscosity, and dp/dx is the pressure gradient, defines completely the viscous flow of homogeneous fluids through porous media of uniform cross section. The permeability constant, k, then is an expression of the properties of a particular porous body which collectively require fluid flow to be controlled by fluid viscosity and pressure gradient in the manner indicated by Eq. (1). Now, in media variously saturated with two or more immiscible continuous fluid phases Darcy's law will still define the dynamic character of flow for each phase separately, if effective permeability constants are properly defined as functions of the distributions of the various saturating fluids. This point of view follows that accepted by Richards[10], who considered the presence of one fluid saturating a porous body merely as a factor which controlled (in the same manner as the structure of the porous body itself) the geometry of the paths available for flow to another immiscible fluid simultaneously saturating the porous body. The analysis to follow requires assuming, as a simplification, steady state flow with the fluid phase saturation distribution uniformly constant during the time interval of measurement; and in the study of reservoir behavior this usually can be done rigorously, at least in principle, by selecting sufficiently small elements for consideration wherein the macroscopic flow character is nonetheless retained. Under such conditions, the observed effective permeabilities become significant constants functionally related to the saturation distribution in addition to the other porous body properties which, as noted above, themselves control completely the dynamic aspects of single-phase (homogeneous fluid) flow.

In developing the basis for the analysis to follow where relative permeability will be explicitly related to saturation distribution characters attention is called to certain previous attempts which have been made to relate specific and effective permeability to various rock properties. Traxler and Baum[11] defined specific permeability in terms of average pore radius, and Leverett[2] attempted to apply this concept to relative permeability. Hassler[3,4] and Botset[5] also discussed this supposed relationship, although none of these authors presented an exact definition of pore distribution, and Leverett[12] finally discarded the notion altogether because of the complicating factors related to saturation hysteresis effects. In this connection, Haines[13], and more recently, Leamer and Lutz[14] and Ritter and Drake[15] showed the usefulness of relating pore distribution to the differential plot of the capillary pressure type relation,‡ implying the possibility of deriving relative permeability relations therefrom, although this has not yet been entirely accomplished§. Carman[16] and others used the Kozeny equation in defining permeability in terms of surface area, porosity, and rock texture, and Krumbein[17] and others have discussed the relationship between permeability and grain size parameters. The recent work of Brownell and Katz[8] considers the connection between relative and specific permeability as based on correlations developed from existing data. Their approach holds great promise, at least for engineering use, particularly if examination of newer data as they become available substantiates the general applicability of their correlations.

These attempts to explicitly relate permeability functions to rock properties can be expressed by the following analytical reasoning. Permeability can be defined functionally as:

$$k = F(T) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

That is, there are a series of rock properties collectively represented by the symbol T which control permeability according to the prevailing physical requirements of the system. In general, the function, F(T), will be known in simple systems (e.g., capillary tube), whereas it will be only partially or imperfectly known in more complex systems (e.g., petroleum reservoir rock). In practice this is a serious limitation to the extent that the approximations which are discovered to apply under one set of conditions become invalid under slightly different conditions such that empirical generalization is impossible. By analogy the effective permeability, k_e, can also be considered as formally defined in terms of other functions of rock properties, where at least one function of particular importance involves the fluid phase saturation distribution, or:

$$k_e = F_e(T_e,\rho), \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where ρ is employed here to denote the saturation distribution of the fluid phases. The relative permeability, k_r, then can be expressed as:

$$k_r = \frac{k_e}{k} = \frac{F_e(T_e,\rho)}{F(T)} \wedge\!\!\vee F_r(\rho) \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Eq. (4) calls attention to the simplification employed in the present treatment of relative permeability, which involves describing all of the properties of the system (responsible for the specific permeability in single phase flow) as implicit functions of saturation in polyphase flow. Therefore, the saturation (or more properly, the saturation distribution) explicitly becomes the only variable controlling relative permeability in polyphase flow, and this concept is developed in the paragraphs to follow. For example, the "effective" porosities* which contribute to the separate elements of polyphase flow can be related to the total porosity responsible for single phase flow according to the character of the prevailing saturation distributions in the polyphase system. Assuming for the moment, for illustrative purposes, that effective porosities and total porosity are the only factors which determine effective permeability and specific permeability respectively, a ratio of these factors as defined in terms of a saturation function will then serve uniquely as an expression for relative permeability.

Having now indicated a need for detailed examination of relative permeability concepts and having suggested a basis for the necessary analysis, extensions will be made below to provide a definition of relative permeability in terms of known saturation parameters. The development as presented in the next section applies principally to a consideration of the *wetting phase* relative permeability relation, although elsewhere in this paper it is shown that non-wetting phase relations and three phase relations also can be inferred, at least approximately, in a similar and related manner.

‡ That is, the plot of some function of the fluid phase distributions versus some measure of the capillary pressure obtaining at the interfaces between phases (e.g. the interfacial curvature, or the height of the interface above some reference level of zero curvature, etc.).

§ c.f. discussion following Eq. (9).

* Effective porosity is herein defined as the saturation of a phase under consideration per unit of bulk volume.

DEVELOPMENT OF THE GENERALIZED EXPRESSION FOR WETTING PHASE RELATIVE PERMEABILITY

In a recent paper[21] the author investigated some of the possible applications of capillary pressure data, and arrived at the following equation for wetting phase relative permeability, as:

$$k_{rw} = \rho_w \left(\frac{P_D}{P_C}\right)^2 \quad \ldots\ldots\ldots \quad (10)$$

Now, in order to contribute to a fuller interpretation of the theoretical considerations; to compensate for notational differences occuring in this paper and the above mentioned Rose and Bruce paper (loc. cit.); and to allow the desired emphasis of dynamical rather than static considerations of fluid behavior, the development of Eq. (10) will be reviewed as follows:

According to common usage the Kozeny equation for a single phase flow can be expressed as:

$$k = \frac{f}{A^2 t} \quad \ldots\ldots\ldots \quad (5)$$

where f is the fractional porosity, A is the specific internal surface area of the pores (per unit of pore volume, and t is a dimensionaless rock textural constant related to the shape and orientation (tortuosity) of the pores. Carman[18] later, in studying the properties of unconsolidated sands, established empirically that:

$$A = \frac{P_D}{\sigma} \quad \ldots\ldots\ldots \quad (6)$$

where P_D is the displacement pressure, and σ is the interfacial tension. Eqs. (5) and (6) can be combined to yield:

$$k = \frac{f\sigma^2}{P_D^2 t} \quad \ldots\ldots\ldots \quad (7)\dagger$$

Now, considering the wetting phase effective permeability (k_{ew}) in a polyphase flow system it can be argued by analogy to Eq. (7) that:

$$k_{ew} = \frac{f_{ew}\sigma^2}{P_C^2 t_{ew}} \quad \ldots\ldots\ldots \quad (8)$$

where the effective porosity, f_{ew}, is defined as noted above; and where P_c, the capillary pressure, is accepted as being the effective displacement pressure characterizing the partially saturated system. The effective rock textural constant, t_{ew}, has not been evaluated as yet, and therefore, for the purposes of this analysis it will be assumed that $t_{ew} = t$ throughout the saturation range of interest.‡ These assumptions made for expediency, however, can be supported by the fact that a plausible conclusion is eventually obtained, as will be seen below. In any event, simply dividing Eq. (8) by Eq. (7) yields an expression for wetting phase relative permeability, k_{rw}, namely:

$$k_{rw} = \frac{k_{ew}}{k} = \left(\frac{f_{ew}}{f}\right)\left(\frac{P_D}{P_C}\right)^2 \left(\frac{t}{t_{ew}}\right) \quad \ldots \quad (9)$$

which leads to Eq. (10) since $t = t_{ew}$ has been assumed, and since $\frac{f_{ew}}{f_w} = \rho_w$.

Eq. (10) can be differentiated to yield:

$$\frac{dk_{rw}}{d\rho_w} = k_{rw}\left(\frac{1}{\rho_w} + \frac{2}{rD_r}\right) \quad \ldots \quad (11)$$

where:
$$D_r = \frac{d\rho_w}{dr} = -\frac{P_C}{r}\frac{d\rho_w}{dP_C}$$

is the pore radii distribution coefficient according to Ritter and Drake (loc. cit.), and r is the pore radius (i.e. a pore width) which under a given condition of saturation (ρ_w) contains the interfaces between the non-wetting and wetting phases.§ Eq. (11) supports the view mentioned above that the relative permeability-saturation relation depends on the distribution of pores in the system being considered.

Actually, Eq. (10) can be derived more fundamentally by combining the Darcy and the Poiseuille equations for fluid flow in the manner suggested by Traxler and Baum (loc. cit.) to yield:

$$k = \frac{f r^2}{\text{const.}}$$

where r is presumed to be an average pore radius of the hypothetical system of capillary tubes equivalent to the porous media actually being considered. By analogy, then, an expression for effective permeability in terms of an effective porosity and a similar effective average pore radius can be derived, which on combination with the above expression for specific permeability yields an expression for relative permeability as:

$$k_r = \rho\left(\frac{r_e}{r}\right)^2 \quad \ldots\ldots\ldots \quad (10a)$$

where r_e refers to the average pore radius of that portion of the system containing the phase under consideration having a saturation, ρ. To the extent that the ratio $(r_e/r)^2$ is related to the distribution of fluids within the interstitial spaces, Eq. (10a) shows how relative permeability depends both on phase saturation and distribution. In order to illustrate the significance of Eq. (10a) Curves E and F (as applied to non-wetting

† Although according to the derivations of Eq. (5), (6), (7), . . . these relations apply strictly to unconsolidated systems [c.f. Sullivan and Hertel[19] point out, for instance, that "where the media are consolidated, or where the media contain bridging, agglomeration or considerable channeling" there is some question as to the applicability of Eq. (5)], it is assumed that suitable adjustment of the rock textural constant, t, will make these relations applicable to a consideration of consolidated systems. Carman has recently discussed the applicability of Eq. (5) to consolidated porous media.[33]

‡ The constant, t, is defined fundamentally[19] as a product of dimensionless pore shape and orientation factors. This *could* suggest that t_{ew} characterizing a polyphase system is approximately equal to the t characterizing the equivalent single-phase system in the sense that the incidental presence of a non-wetting phase does not appreciably alter the configurational properties of the pores containing the wetting phase, although its presence does reduce the porosity available for wetting phase saturation.

§ Note, a plot of r versus ρ_w will exhibit the same hysteresis effects observed in the capillary pressure-saturation relation.

and wetting phase relative permeability respectively) are presented in Fig. 6, as calculated for a hypothetical case where it is assumed that a normal probability distribution of pores obtains and that at any given phase saturation condition the wetting phase is always contained in the smallest pores and the non-wetting phase is always contained in the largest pores. The shapes of these Curves E and F in Fig. 6 will be referred to later. In any event, it is noted that when considering wetting phase relative permeability Eq. (10a) reduces to Eq. (10) if use is made of the following well-known relations:

$$P_D = F(\sigma/r) \quad \text{and} \quad P_C = F(\sigma/r_e).$$

In order to solve Eq. (10) it is necessary to have available pressure versus saturation data such as are obtained in capillary pressure (static) experiments or displacement (dynamic) experiments.* It will be shown now, however, that a more general solution of the wetting phase relative permeability versus saturation relation can be derived, where the relative permeability is entirely described in terms of explicitly known saturation parameters. This has been accomplished conveniently by observing the properties of the family of curves produced by plotting the dimensionless group:

$$\phi(\rho_w) = \rho_w \left[\frac{P_D}{P_D + \int_{\rho_w}^{1} P_C \, d\rho_w} \right]^2 \quad . \quad . \quad . \quad . \quad . \quad (12)$$

versus the wetting phase saturation, ρ_w.† The dimensionless group, $\Phi(\rho_w)$, itself was evolved by treating the Kozeny equation (Eq. (5)) in a manner similar to the derivation of Eq. (10) from Eq. (7); that is, by assuming $t = t_{ew}$ through the saturation range of interest, and by recognizing that: $f_{ew}/f = \rho_w$. Thus, by analogy to Eq. (5):

$$k_{ew} = \frac{f_{ew}}{A_{ew}^2} \, \frac{1}{t_{ew}}$$

or:

$$k_{rw} = \rho_w \left(\frac{A}{A_{ew}} \right)^2, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

where A_{ew} may be regarded as the effective surface separating the wetting phase from all other elements of the system. Comparison of Eq. (13) with Eq. (10) shows that:

$$A_{ew} = \frac{P_C}{\sigma} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

is a reasonable definition for this effective surface area,§ analogous to Carman's definition of specific surface area, (cf. Eq. (6)).

Eq. (13) also suggests the importance of the function $\Phi(\rho_w)$ on identifying A_{ew} with:

$$A + \frac{1}{\sigma} \int_{\rho_w}^{1} P_C \, d\rho_w = \frac{P_D}{\sigma} + \frac{1}{\sigma} \int_{\rho_w}^{1} P_C \, d\rho_w \ ,$$

where:

$$\frac{1}{\sigma} \int_{\rho_w}^{1} P_C \, d\rho_w$$

is the interfacial surface area previously defined by Leverett.[12]

It will be noted from Eq. (12) that $\Phi(\rho_w)$ has the following properties:

$$\lim_{\rho_w \to 1} \frac{d}{d\rho_w} \Phi(\rho_w) = 3,$$

since:

$$\lim_{\rho_w \to 1} \Phi(\rho_w) = 1, \text{ and } \lim_{\rho_w \to 1} P_C = P_D \quad . \quad . \quad . \quad (15)$$

Also:

$$\lim_{\rho_w \to \rho_{wi}} \Phi(\rho_w) = 0,$$

if it is assumed that:

$$\lim_{\rho_w \to \rho_{wi}} P_C = \lim_{\rho_w \to \rho_{wi}} \int_{\rho_w}^{1} P_C \, d\rho_w = 00,$$

where the irreducible minimum wetting phase saturation, ρ_{wi} is defined as:

$$\lim_{k_{rw} \to 0} \rho_w = \rho_{wi}$$

Fig. 1 shows a plot of $\Phi(\rho_w)$ versus ρ_w obtained from capillary pressure data, as previously presented in the cited literature references[4,12,20,21,22]. The general conformance of these experimental curves to the above outlined limiting conditions suggests the possibility of explicitly relating $\Phi(\rho_w)$ to the saturation parameters ρ_w and ρ_{wi}. This has been accomplished in the following manner.

First, the analogy between an assemblage of capillary tubes and porous systems of the type which constitute petroleum reservoir rock is accepted as applicable to the purposes of this analysis (cf. Brownell and Katz[5] have recently stated a similar

* It is developed later in this paper that terms which are the dynamic equivalents of capillary and displacement pressure can be substituted in Eq. (10) to define dynamically the relative permeability relation. The necessity of this extension is suggested by examining, for instance, Leverett's capillary pressure and relative permeability data obtained on unconsolidated sands.[2,12] It will be seen that these data are not interrelated through Eq. (10), since the capillary pressure data describe fluid distribution in Leverett's systems under *static* conditions and the relative permeability data pertain specifically to *dynamic* conditions. In order, then, to employ Eq. (10) it is necessary to know the capillary pressures obtaining at the interfaces under the dynamic conditions of fluid phase distribution in the flowing system. The fact that these conditions of fluid distribution exhibit hysteretic behavior suggest that the relative permeability relation itself will be characterized by a related hysteresis, one limit of which it may be supposed will be that described by Eq. (10) when static capillary pressure data are substituted therein.

† It may be noted that Eq. (12) and the general considerations given here leading to its development but with special emphasis on its implications with respect to capillary pressure phenomena have also been presented by Rose and Bruce.[21]

§ Comparison of Eq. (13) with Eq. (10) implies that the effective surface area, A_{ew}, increases indefinitely as the wetting phase saturation is decreased to its minimum value. This simply means that in the process of desaturation the wetting phase is confined to smaller and smaller pores where the surface to volume ratio becomes larger and larger.

view, as have numerous others previously). It is further supposed that all porous systems of the type being considered can be classed, according to their fluid behavior properties, as intermediate between the limiting systems described as uniform sized, uniformly oriented capillary tubes on the one hand, and random sized, randomly oriented capillary tubes on the other. These two limiting systems, abbreviated U.S.O. and R.S.O. respectively, can be analyzed in detail as follows:

The uniform sized, uniformly oriented system of capillary tubes (which is actually equivalent to a single capillary tube oriented in the direction of flow) has this character as defined in terms of capillary pressure concepts. The capillary pressure equals the displacement pressure for all values of saturation,‡ and the irreducible wetting phase saturation in zero. It follows then that:

$$\int_{\rho_w}^{1} P_C \, d\rho_w = P_D \, (1-\rho_w),$$

Or, by Eq. (12):

$$\Phi(\rho_w)_{U.S.O.} = \frac{\rho_w}{(2-\rho_w)^2} \quad . \quad . \quad . \quad . \quad . \quad (16)$$

Eq. (16) satisfies the limiting requirements of Eq. (15).

The random sized and oriented system of capillary tubes (R.S.O.) simply is characterized by the fact that $\rho_{w1} = \frac{2}{3}$, since it is supposed that the random orientation reduces two-thirds of the pore volume effectively to *cul-de-sac* porosity (i.e., porosity which cannot be invaded by the non-wetting phase since the zero permeability conditions prevent the escape of the wetting phase therefrom).* Now, it is observed from Eq. (15) that the intercept on the ρ_w axis of the tangent to

$$\lim_{\rho_w \to 1} \frac{d}{d\rho_w} \Phi(\rho_w) \text{ is also } \frac{2}{3} \text{ such that the curve}$$

$$\Phi(\rho_w)_{R.S.O.} = (3\rho_w - 2) \quad . \quad . \quad . \quad . \quad . \quad (17)$$

is taken as the most convenient definition for $\Phi(\rho_w)_{R.S.O.}$. It is readily vertified that Eq. (17) also satisfies the requirements of Eq. (15).

The limiting functions $\Phi(\rho_w)_{U.S.O.}$ and $\Phi(\rho_w)_{R.S.O.}$ are shown in Fig. 1, and, as assumed above, data obtained on any porous system should yield $\Phi(\rho_w)$ versus ρ_w plots belonging to the family of curves intermediate to these limts and having the properties indicated by Eqs. (15). A suitable generalized expression for $\Phi(\rho_w)$ which fits the required conditions stated above, and which serves as a basis for deriving the desired expression for relative permeability, is:

$$\Phi(\rho_w) = \frac{4(\rho_w - \rho_{w1})(1-\rho_{w1})}{[(3\rho_{w1}-2)\ \rho_w + (4-5\ \rho_{w1})]^2} \quad . \quad . \quad . \quad (18)$$

Eqs. (12) and (18) can now be combined to yield:

$$\frac{P_C}{P_D} = \frac{2\rho_w^2(2-3\rho_{w1}) + 3\rho_w\ \rho_{w1}(3\rho_{w1}-2) + \rho_{w1}(4-5\rho_{w1})}{4\sqrt{\rho_w(1-\rho_{w1})\ (\rho_w-\rho_{w1})^3}} \quad (19)$$

It will be observed that the conditions:

$$\lim_{\rho_w \to 1} P_C = P_D \quad \text{and} \quad \lim_{\rho_w \to \rho_{w1}} P_C = 00$$

are satisfied by Eq. (19). Combining Eq. (19) with Eq. (10), we obtain finally:

$$k_{rw} = \frac{16\rho_w^2\ (\rho_w-\rho_{w1})^3\ (1-\rho_{w1})}{[2\rho_w^2(2-3\rho_{w1}) + 3\rho_w\ \rho_{w1}\ (3\rho_{w1}-2) + \rho_{w1}(4-5\rho_{w1})]^3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

where Eq. (20) evidently reduces to the limiting values 1 and 0, as ρ_w approaches 1 and ρ_{w1} respectively.

While Eq. (19) has been developed primarily as an intermediate relationship for the purpose of deriving Eq. (20), it has the same type of validity as the empirical representation of capillary pressure data by the function $\Phi(\rho_w)$ plotted in Fig. 1. It is not suggested that Eq. (19) gives a universal description of capillary pressure curves, although, in contrast to other proposed empirical equations,† it satisfies all the basic

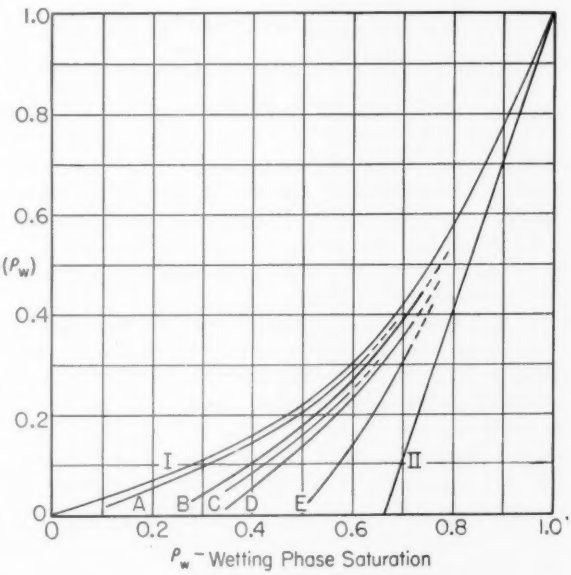

FIG. 1 — VARIATION OF THE RHO FUNCTION WITH WETTING PHASE SATURATION.

Curve I — Theoretical Curve applying to a U.S.O. system.
Curve II — Theoretical Curve applying to a R.S.O. system.
Curve A — Experimental Curve for Leverett's Sand III[12].
Curve B — Experimental Curve for an Ohio Sandstone.[20]
Curve C — Experimental Curve for a Magnolia Limestone.[21]
Curve D — Experimental Curve for Thornton and Marshall "Well A".[22]
Curve E — Experimental Curve for a California Sand.[4]

‡ Starting with a completely saturated capillary tube a displacing pressure which is infinitesimally greater than P_D is required before the non-wetting phase can enter the capillary and produce a desaturation of the wetting phase. However, at any saturation condition between 1 and 0, the pressure difference between the phases arbitrarily can be set exactly equal to P_D, thereby establishing condition of statis equilibrium, so that $\frac{d_{PC}}{d\rho_w} = 0$.

* Klinkenberg[23] in his analysis of homogeneous flow through an R.S.O. system makes a similar sort of an assumption.

† c.f. for example, the equation of Hassler *et al* (loc. cit.).

physical requirements as expressed by Eq. (15). It is Eq. (20) which represents the immediate goal of the above outlined theoretical considerations. Its validity and usefulness will be discussed below.

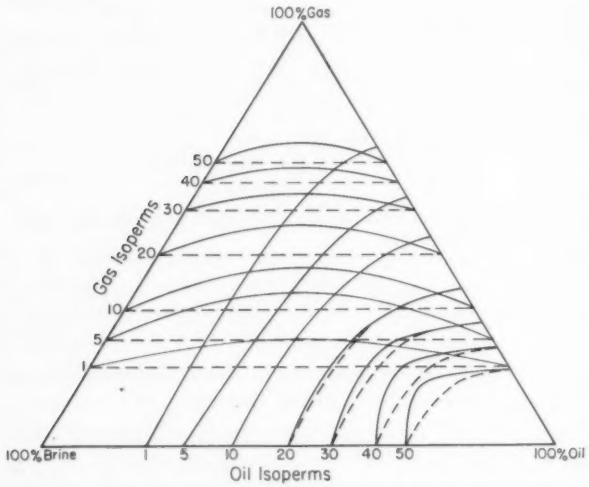

FIG. 2 — THREE-PHASE RELATIVE PERMEABILITY DIAGRAMS.
Solid Lines, Data of Leverett and Lewis.[24]
Dashed Lines, Theoretical Gas and Oil Isoperms.
(Water Isoperms not shown.)

DISCUSSION OF RELATIVE PERMEABILITY CONCEPTS SUGGESTED BY AVAILABLE EXPERIMENTAL DATA

First, however, in order to develop the range of usefulness in which relationships of the type indicated by Eq. (20) can be applied to evaluate relative permeability, some consideration will be given to the published empirical results of previous workers. This is required, since the validity of Eq. (20) is not to be considered as rigorously proved by the above argument, so that conformance between theory and experiment is the only direct proof presently available. One danger in this approach to be noted and avoided stems from the uncertainty regarding the detail which justifiably can be employed in the examination of the data, since it is desired only to generalize on significant features independent of the experimental procedures followed and the experimental materials employed.‡

The data of Leverett and Lewis[24] which have been replotted in Fig. 2 for convenience provide an indication of the type of relative permeability relations which prevail in two and three phase systems. Although this work pertains specifically to the properties of unconsolidated media, the conclusions applying to two-fluid-phase systems are confirmed more or less by later studies of consolidated sand bodies. The conclusions applying to three-fluid-phase systems, however, have not yet been shown valid when applied to consolidated sands, and in the discussion to follow this fact is recognized to the extent that certain of the Leverett and Lewis statements about three-fluid-phase systems will not be accepted simply because available data or intuitive argument does not require unqualified acceptance.

The data of Leverett and Lewis suggest that the following qualitative generalizations, expressed symbolically,§ apply insofar as gross features are concerned to a consideration of the properties of a given porous body:

$$\frac{k_{rb}\ (\rho_b)}{\text{b-g system}} = \frac{k_{rb}\ (\rho_b)}{\text{b-o system}} = \frac{k_{rb}\ (\rho_b)}{\text{b-o-g system}} \quad \ldots \quad (21\text{-}1)$$

That is, the relative permeability to brine in a given porous body is independent of the fluid properties of the other saturating fluid(s) in those cases where brine is considered to be the wetting phase.

Also:

$$\frac{k_{rg}\ (\rho_g)}{\text{g-b system}} = \frac{k_{rg}\ (\rho_g)}{\text{g-o system}} > \frac{k_{rg}\ (\rho_g)}{\text{g-o-b system}} \quad \ldots \quad (21\text{-}2)$$

That is, the relative permeability to gas in two phase systems is independent of the nature of the wetting phase, and in three phase systems it is always less at a given saturation than in a two phase system.

Finally:

$$\frac{k_{ro}\ (\rho_o)}{\text{o-g system}} < \frac{k_{ro}\ (\rho_o)}{\text{o-b system}} \lessgtr \frac{k_{ro}\ (\rho_o)}{\text{o-g-b system}} > \frac{k_{ro}\ (\rho_o)}{\text{o-g system}} \quad (21\text{-}3)$$

That is, at a given oil saturation, the relative permeability to oil is less in an oil-gas system than in an oil-brine system; the latter itself being greater than, equal to, or less than the oil relative permeability in a three-phase system; the oil relative permeability in the three-phase system in turn being always greater than that in a two-phase oil-gas system.

Now, to the extent that gas and oil can both be regarded as non-wetting phases in brine-oil or brine-gas two-phase systems, and to the extent that appropriate compensation is made for gas slippage (Klinkenberg) effects,* it is regarded that:

$$\frac{k_{rg}\ (\rho_g)}{\text{g-b system}} = \frac{k_{rg}\ (\rho_g)}{\text{g-o system}} = \frac{k_{ro}\ (\rho_o)}{\text{o-b system}} \quad \ldots \quad (21\text{-}4)$$

‡ It is significant to note that all the cited references on permeability measurement emphasize the exploratory nature of the work as a precaution against the tendency to over-generalize on the experimental results.

§ The following symbols are employed as subscripts:
b refers to a brine (aquous) phase
g refers to a gas phase
o refers to an oil phase
n refers to a non-wetting phase (unspecified)
w refers to a wetting phase (unspecified)
Thus, the notation:

$$\frac{k_{rb}\ (\rho_b)}{\text{b-g system}}$$

implies we are concerned with the relative permeability of brine plotted as a function of brine saturation, in a brine-gas (two-phase) system.

* Detailed consideration has been given to the problem of slippage effects in gas relative permeability phenomena, and it has been concluded that these effects are often negligible as an approximation even in instances where appreciable slippage corrections must be applied to the values of effective and specific permeability used to calculate the relative permeability relation. The theory and data supporting this result have been reported elsewhere,[22] together with a statement of the slippage term which must be employed when it is desired to derive *exactly* gas relative permeability as a function of gas mean free path.

this being more or less supported by experimental data.† Also, since oil can be regarded as a wetting phase in a two-phase oil gas system Eq. (21-1) can be expanded as:

$$\frac{k_{ro}\ (\rho_o)}{\text{o-g system}} = \frac{k_{rb}\ (\rho_b)}{\text{b-g system}} = \frac{k_{rb}\ (\rho_b)}{\text{b-o system}} = \frac{k_{rb}\ (\rho_b)}{\text{b-o-g system}} \quad (21\text{-}5)$$

On combining the equalities (21-4) and (21-5) with the inequalities (21-2) (and 21-3) we obtain:

$$\frac{k_{rn}\ (\rho_n)}{\text{2-phase system}} > \frac{k_{rw}\ (\rho_w)}{\text{2 or 3-phase system}} < \frac{k_{ro}\ (\rho_o)}{\text{o-g-b system}} \lessgtr \frac{k_{rn}\ (\rho_n)}{\text{2-phase system}} > \frac{k_{rg}\ (\rho_g)}{\text{g-o-b system}} \quad . \quad (21\text{-}6)‡$$

Eq. (21-6) shows how in a given porous body the relative permeability to the three phases, brine, oil and gas, compare with each other under conditions of two and three-phase saturation. Specifically, it is shown that of the nine possible systems of interest those pertaining to wetting phase relative permeability in 2 or 3-phase systems can be classed together, as can those pertaining to non-wetting phase relative permeability in 2-phase systems.§ The relative permeabilities to gas and to oil in 3-phase systems according to presently available data provide an anomolous situation insofar as their description by the inequality (21-6) is not supported by theory nor entirely confirmed by experiment,* and this will receive discussion below. However, first it will be shown how the various elements of Eq. (21-6) can be evaluated, at least approximately, from a consideration of various modified forms of Eq. (20).

APPLICATION OF THE GENERALIZED EXPRESSIONS FOR RELATIVE PERMEABILITY

Fig. 3 shows a plot of Eq. (20) where various values for the term, $\rho_{w\,i}$, are assumed arbitrarily in the interval 0 to 2/3. Also shown for comparison are the representative wetting phase relative permeability data of Botset (loc. cit.), Martinelli *et al*[27], Morse *et al* (loc. cit.), and Bulnes and Fitting[28]. A certain conformance is noted immediately between the shape and character of the experimental and theoretical curves, this conformance being of particular interest because the cited data were obtained variously in studies of several dissimilar porous systems (i.e. capillary tube, unconsolidated sands, consolidated sands and dolomites).

Now it has been mentioned that Eq. (20) was developed specifically as an expression for wetting phase relative permeability. In this connection it should be observed that Eq. (20) conforms to the experimental conclusion first reached by Wyckoff and Botset and later by Leverett and Lewis, that wetting phase relative permeability in a given porous body is a function of saturation alone (independent of fluid properties) as expressed by the relation (21-5). Therefore, by insertion of suitable saturation terms in Eq. (20) it may be assumed that the brine relative permeability in 2 and 3-phase systems and the oil relative permeability in oil-gas systems will thereby be established.†

At this point it becomes necessary to consider an apparent

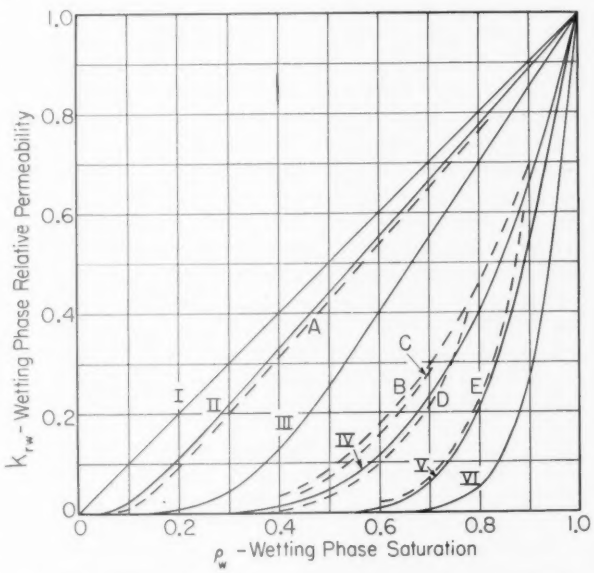

FIG. 3 — EXAMPLES OF WETTING PHASE RELATIVE PERMEABILITY.

Theoretical Curves (Eq. 20).

I. $\rho_{w\,i}$ *assumed to be zero.*
II. $\rho_{w\,i}$ *assumed to be 0.01.*
III. $\rho_{w\,i}$ *assumed to be 0.1.*
IV. $\rho_{w\,i}$ *assumed to be 0.3.*
V. $\rho_{w\,i}$ *assumed to be 0.5.*
VI. $\rho_{w\,i}$ *assumed to be 0.67 (⅔)*

Experimental Curves:

A. Data obtained on single capillary tube[27].
B. Data obtained on unconsolidated sand[9].
C. Data obtained on a synthetic core[25].
D. Data obtained on a dolomite[28].
E. Data obtained on a consolidated sand[2].

† Actually, this question is not entirely settled since the recent data[25,26] in some instances suggest a dependence of the relative permeability on fluid properties. This paper does not consider systems where there is interaction between solid and liquid phases (e.g. clay hydration), it being assumed that in the absence of such interaction the flow of fluids will be controlled entirely by preferential wettability characteristics rather than by incidental fluid properties such as viscosity, etc.

‡ That is, k_{rn} at a given saturation, ρ_n, in 2-phase systems will be greater than k_{rw} at an equivalent saturation, ρ_w, in 2 or 3-phase systems; which in turn is less than k_{ro} at an equivalent saturation, ρ_o, in 3-phase systems; which in turn is greater than, less than or equal to above mentioned k_{rn} in two-phase systems; which in turn is greater than k_{rg} at ρ_g in a g-o-b system.

§ These are:

(1) k_{rb} in b-o system
(2) k_{rb} in b-g system
(3) k_{rb} in b-g-o system
(4) k_{ro} in o-b system
(5) k_{ro} in o-g system
(6) k_{ro} in o-g-b system
(7) k_{rg} in g-b system
(8) k_{rg} in g-o system
(9) k_{rg} in g-o-b system

(1), (2), (3) and (5) may be expressed as k_{rw} in 2 or 3-phase systems. (4), (7) and (8) may be expressed as k_{rn} in 2-phase systems.

* In this connection, it is observed that the Leverett and Lewis data (representing all that is presently known about relative permeability in 3 fluid phase systems) merely support but in no way confirm or establish Eq. (21-6) above, even for the unconsolidated systems they specifically studied, as can be seen simply by replotting the ternary diagrams they reported. This observation, of course, does not detract from the pioneering accomplishment of their experimental work, or from the qualitative importance of their conclusions except where a theoretical contradiction can be established.

† Here and elsewhere in this paper hydrophilic interstitial surfaces have been assumed merely to simplify the presentation.

discrepancy between existing data and the generally accepted theoretical concept symbollically stated as:

$$\lim_{\rho_w \to \rho_{wi}} k_{rw} = 0 \quad \text{where} \quad \lim_{P_C \to 00} \rho_w = \rho_{wi}$$

In the development of Eq. (20) the validity of this concept was assumed and the difficulty arises from the fact that *apparently* in the general case:

$$\lim_{\rho_w \to \rho_{wm}} k_{rw} = 0 \quad \text{where } \rho_{wm} > \rho_{wi} \quad \text{(usually)}$$

For example, an examination of Leverett's capillary drainage experimental data[12] gives values of ρ_{wi} between 5 and 10 per cent, and these are to be compared with ρ_{wm} values of 20-30 per cent elsewhere reported on similar sands[2,6,24]‡. This apparent discrepancy is normally explained by assuming that the relative permeability at saturation ρ_{wm} is so small that it is mistaken for zero, and that actually conditions of pendular configuration must be attained (i.e. $\rho_w = \rho_{wi}$) before flow will cease and relative permeability will become zero.

Although this explanation is plausible, it is of interest to consider another point of view. Fig. 3 in the recent paper by Holmgren[20] calls attention to the fact frequently observed in the laboratory, that the production of a wetting phase from a porous system, effected by the displacing action of an invading non-wetting phase under pressure, depends upon various factors associated with the conditions of flow, and that maximum production will be attained generally in the static type capillary pressure experiment rather than in a dynamic flow type experiment. It seems reasonable that ρ_{wm} can be accepted as the dynamic equivalent of ρ_{wi}, which itself is an "irreducible" saturation attained only under conditions of static equilibrium. In this sense ρ_{wm} is not a fixed and unique saturation, but rather it is determined by the prevailing conditions of flow, and it becomes equal to ρ_{wi} only in the limiting case. Therefore, it will be assumed that ρ_{wm} is an appropriate value to substitute in Eq. (20) when the conditions of polyphase flow are such that $\rho_{wm} \gg \rho_{wi}$, and indeed this is required if Eq. (20) is to be accepted as a suitable generalized expression for wetting phase relative permeability. Thus, Eq. (20) is rewritten as:

$$k_{rw} = \frac{16\rho_w^2 \ (\rho_w - \rho_{wm})^2 \ (1 - \rho_{wm})}{[2\rho_w^2(2 - 3\rho_{wm}) + 3\rho_w\rho_{wm}\ (3\rho_{wm} - 2) + \rho_{wm}\ (4 - 5\rho_{wm})]^2} \quad \ldots\ldots\ldots \quad (22)\S$$

‡ Similar experimental discrepancies have been elsewhere noted. Recent capillary pressure experiments on Nichols Buff sandstone indicate ρ_{wi} values considerably lower than ρ_{wm} values obtained by the extrapolation of Botset's[2] relative permeability data. Fig. 16 of the paper by Bulnes and Fitting (loc. cit.) illustrates this discrepancy as applied to limestones.

§ According to these views, Eq. (10) must also be rewritten as: $k_{rw} = \rho_w \left(\frac{\pi_D}{\pi_C}\right)^2$ where π_D and π_C are the dymanic equivalents of the static quantities, P_D and P_C respectively. In general, it will be found that for a given saturation $\pi_C > P_C$ and that $\pi_D > P_D$, which simply means that an interface in motion in a pore of a given size will have a larger specific surface area than the same interface in the same pore under conditions of static equilibrium. (In this connection, note that Eq. (10) was developed to apply to a *draining* system, i.e. one where ρ_w is always constant or decreasing in magnitude. Similar argument, however, can be applied also to an imbibing system, suggesting the possibility of extremely complex hysteresis effects). Eq. (19) then can be rewritten as:

$$\frac{\pi_C}{\pi_D} = \frac{2\rho_w^2(2 - 3\rho_{wm}) + 3\rho_w\rho_{wm}\ (3\rho_{wm} - 2) + \rho_{wm}\ (4 - 5\rho_{wm})}{4\sqrt{\rho_w(1 - \rho_{wm})\ (\rho_w - \rho_{wm})^3}}$$

in accordance with these views.

Fig. 4 is presented to illustrate the significance of the various saturation parameters employed in this paper. It is evident that whether ρ_{wm} is used in Eq. (22) or whether ρ_{wi} is used in Eq. (20) to derive relative permeability, this will depend upon the nature of the flow process being considered. Further, it is believed that these limiting saturation parameters can be approximated from existing data correlations* or experimentally obtained in a manner less involved than present methods of relative permeability measurement.† This is illustrated with the aid of Fig. 5 where an assumption is made (based on Botset's[2] plot of gas-oil ratios) that 0.5 is a suitable value to use for ρ_{wm} when it is desired to fit Eq. (22) to Botset's data as obtained under his stated flow conditions. This gives curve "A" in Fig. 5, and for comparison Botset's original Nichols Buff data points are included. Also shown in Fig. 5 is a plot of Eq. (20) where ρ_{wi} is chosen to be 0.35 (curve "B"). Since this value ($\rho_{wi} = 0.35$) is a reasonable "irreducible" saturation for the Nichols Buff sand, it is concluded that curve "B" shows a limiting position of the relative permeability relation, which would characterize this sand under conditions quite different from those experimentally imposed by Botset.‡

In concluding this discussion on the applicability of Eqs. (20) and (22) to the evaluation of k_{rw}, it is of interest to note that these equations reduce to:

$$k_{rw} = \rho_w \text{ or } \frac{dk_{rw}}{d\rho_w} = 1 \quad \ldots\ldots \quad (22a)$$

when the condition: $\rho_{wm} = \rho_{wi} = 0$ is satisfied, as identified with a system of uniformly sized capillary tubes oriented in the direction of flow. Eq. (22a) is of particular interest in connection with Leverett's argument[2] where he concludes that relative permeability curves characterizing "a system of non-interconnected, parallel capillary tubes" will be simply 45° lines when plotted conventionally (i.e. as in Fig. 3) according

* In this connection, Brownell and Katz[5] develop the relation:

$$\rho_{wm} = \frac{1}{86.3}\left(\frac{k}{G\sigma\cos\theta}\frac{dp}{dx}\right)^{-0.264}$$

where G is the acceleration due to gravity and θ is the angle of contact. Now, this implies that the term ρ_{wm} is determined by the pressure gradients in the flowing phases, requiring (acording to a strict interpretation of the equations appearing in this paper) that in some instances at least the entire relative permeability curve will be shifted upon variation in the pressure gradients. Experimental evidence of such possibilities as applied to non-wetting phase relative permeability can be found by examining Fig. 4 of the recent paper by Henderson and Yuster (loc. cit.). Actually, more recently at the 1948 Annual Conference on Secondary Recovery at the Pennsylvania State College these authors presented additional indications of such hysteretic shifts as applied to either wetting or non-wetting phases relative permeability, these shifts being entirely in accord with the theoretical interpretation presented in the legend for Fig. 4 of this paper (Private Communication, October 16, 1948). The recent paper of Childs and George gives further evidence of these hysteretic shifts.[24]

† For instance, ρ_{wi} is simply the irreducible saturation observed in a drainage type capillary pressure experiment; that is, the maximum saturation where the wetting phase configuration is still entirely pendular.

‡ Curve "D" illustrates what might be expected if Nichols Buff capillary pressure data were used in Eq. (10) to describe wetting phase relative permeability. The deviation between curves B and D supports the view that *dynamic* flow data are not directly derivable from static capillary pressure data.

to the assumed requirement that in such a system the sum of the effective permeabilities for the separate phases should total the specific permeability. Although as Henderson and Yuster[26] have recently pointed out the experimental data of Martinelli *et al*[27] do not confirm Leverett's prediction,§ at least the equations developed in this paper are in accord with the concept that in the absence of capillary interaction between immiscible fluid phases (as would prevail, for instance, in a hypothetical U.S.O. system of the type above mentioned) phase relative permeability is linearly related to phase saturation (c.f. Eq. (22a)).

Having indicated the usefulness of Eq. (20) and (22) to evaluate wetting phase relative permeability under the conditions described by Eq. (21-5) when reasonable values for ρ_{wi} (or ρ_{wm}) can be assumed or otherwise obtained, it is of interest now to see what further extensions can be made in the manner of evaluating specific non-wetting phase relations under the 2-phase saturation conditions described by Eq. (21-4).

It has been observed that if we define Ψ_w as the limiting wetting phase saturation associated with $k_{rn}(1)$; and then if we arbitrarily define the "effective" non-wetting phase saturation range of interest to be within the interval, $\rho_w(1)$ and $\rho_w(\Psi_w)$; and then if we substitute in Eq. (22) the effective non-wetting saturation terms so defined for the comparable wetting phase saturation terms; an expression is evolved which apparently can serve as an equation for non-wetting phase relative permeability according to the conformance with experimental data indicated in Fig. 5 (Curve "C") and Fig. 6.* Thus,

$$\lim_{k_{rn}\to 1} \rho_w = \Psi_w \qquad \text{(Definition)}$$

Also,

$$\rho_{en} = \frac{\rho_n}{1-\Psi_w} = \frac{1-\rho_w}{1-\Psi_w} \qquad \text{(Definition)}$$

$$\rho_{enm} = \frac{\rho_{nm}}{1-\Psi_w}$$

where ρ_{nm} will be identified with equilibrium non-wetting phase saturation as commonly defined. Then by analogy to Eq. (22):

$$k_{rn} = \frac{16\rho_n^2(\rho_n-\rho_{nm})^3(1-\Psi_w-\rho_{nm})}{[2\rho_n^2(2-2\Psi_w-3\rho_{nm})+3\rho_n\rho_{nm}(3\rho_{nm}-2+2\Psi_w)+\rho_{nm}(1-\Psi_w)(4-\Psi_w-5\rho_{nm})]^2} \qquad (23)$$

where,

$$\lim_{\rho_w\to\Psi_w} k_{rn} = \lim_{\rho_n\to(1-\Psi_w)} k_{rn} = 1$$

and

$$\lim_{\rho_n\to\rho_{nm}} k_{rn} = 0.$$

§ Nor do these data deny Leverett's prediction since it may be supposed that the conditions of the Martinelli *et al* experiment are not entirely applicable to a consideration of phenomena occurring in Leverett's idealized system.

* Attention is called to the recent gas relative permeability data reported by the author[22] where conformance between the results of experimentation and the theoretical analysis as presented above also has been obtained.

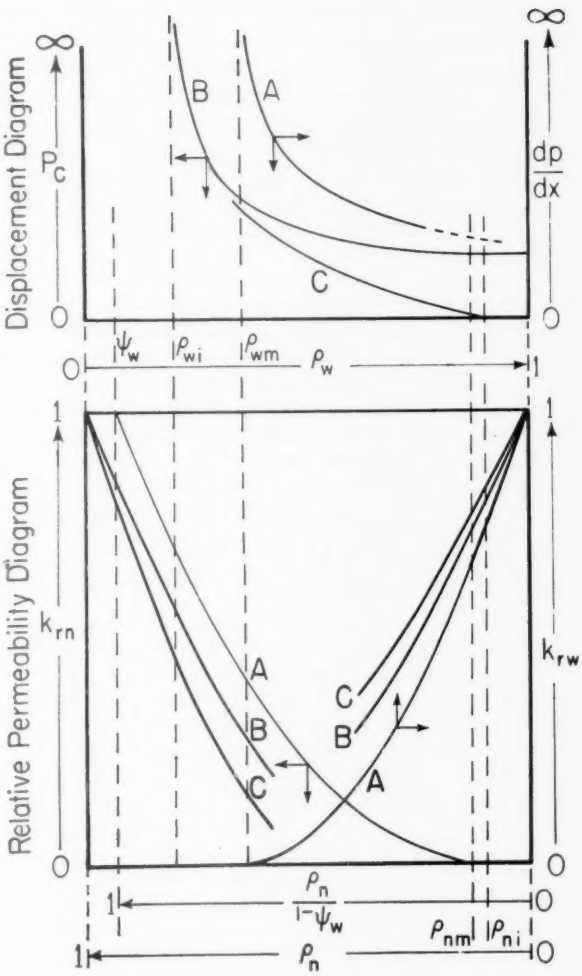

FIG. 4 — DEFINITIONS OF SATURATION PARAMETERS.

Curves A, B, and C refer to the plots of a dependent variable versus some function of fluid saturation as the independent variable. In the top diagram the dependent variable is either the capillary pressure difference measured across the interfaces of contact between the immiscible fluids saturating the interstitial spaces, or some function of the pressure gradients existing in these phases when they are flowing. In the bottom diagram the dependent variable is either the wetting phase or the non-weting phase relative permeability. In particular, Curves A refer to fluid distributions obtaining under conditions of dynamic equilibrium (that is, under conditions of steady-state heterogeneous flow of immiscible fluids). Curves B and C refer to fluid distributions obtaining under conditions of static equilibrium which have been approached respectively by drainage or by imbibition capillary pressure processes. Thus, any given group of Curves A, B, and C show possible limits of hysteresis in the relation associated with these curves. Note, for instance, that the fluid distribution which yields the largest value for non-wetting phase relative permeability (at a given non-wetting phase saturation) invariably yields the lowest value for wetting phase relative permeability, and vice versa.

Thus, in the derivation of Eq. (23) the existence of limiting non-wetting phase saturation terms, ρ_{n1} and ρ_{nm}, analogous to the wetting phase terms, ρ_{w1} and ρ_{wm}, has been implied, as shown graphically by Fig. 4 and as discussed in greater detail below.

The manner in which existing experimental data are described by Eq. (23), of course, can be fortuitous, to the extent that insufficient data are available for examination. However, the applicability of Eq. (23) itself can be developed in a reasonable manner from more or less plausible concepts as follows:

In the first place, Brownell in his discussion of the Martinelli *et al* paper (loc. cit.), and later Brownell and Katz (loc. cit.) develop the view that the pore space saturated wtih capillary bound (immobile) wetting phase should be eliminated from definitions of saturation functions employed in flow equations. It is evident that if we identify the term Ψ_w defined above with the immobile wetting phase saturation, then the terms,

$$\frac{\rho_n}{1-\Psi_w} \quad \text{and} \quad \frac{\rho_{nm}}{1-\Psi_w}$$

which were substituted in Eq. (22) to yield Eq. (23) actually express non-wetting phase saturation parameters per unit of pore volume from which the portion occupied by the immobile wetting phase has been eliminated.†

This discussion suggests that a character of symmetry is a common feature associating wetting and non-wetting phase relative permeability to each other, for it is evident that a comparison of Eqs. (22) and (23) will yield:

$$k_{rw}(\rho_w) = k_{rn}(\rho_n)$$

when:

$$\rho_w = \rho_n$$

in a 2-phase system where: $\Psi_w = 0$ and where: $\rho_{wm} = \rho_{wi}$. Physically, a condition of symmetry probably requires assuming that relative permeability is a function of saturation alone, and that "effectively" the pore configuration may be represented as an assemblage of equivalent capillary tubes. Thus, when a little non-wetting phase is introduced into an initially non-wetting phase saturated system it occupies several of the smaller pores, so that it is not unreasonable that a decrease in the non-wetting phase relative permeability should result approximately equivalent to the above referred to decrease in wetting phase relative permeability. (Note, how-

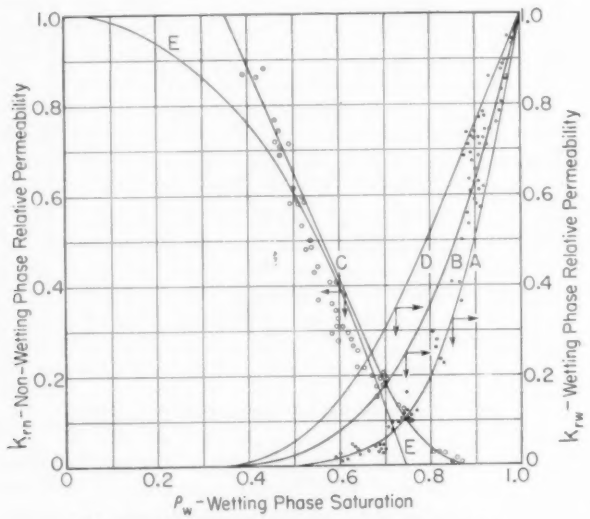

FIG. 5 — CONFORMANCE OF EXPERIMENTAL DATA TO THEORETICAL PREDICTIONS.

Curve A — Theoretical Curve obtained by assuming $\rho_{wm} = 0.5$ in Eq. (22) in order to fit Botset's brine relative permeability data[3] on Nichols Buff (solid points).

Curve B — Theoretical Curve obtained by assuming $\rho_{w1} = 0.35$ in Eq. (20) to show the limiting position of the brine relative permeability relation.

Curve C — Theoretical Curve obtained by assuming $\psi_w = 0.35$, $\rho_{nm} = 0.1$ in Eq. (23) in order to fit Botset's gas relative permeability data[3] on Nichols Buff (circled points).

Curve D — Description of Nichols Buff "brine" relative permeability as suggested by Eq. (10).

Curve E — Description of Nichols Buff "gas" relative permeability data as suggested by Eq. (10a), where a normal probability distribution of pores is assumed and where Eq. (10a) is normalized to show a zero relative permeability at an asumed value for the equilibrium gas saturation.

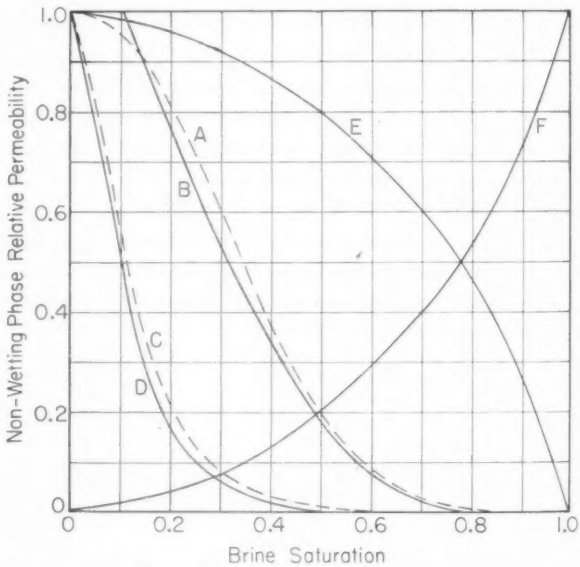

FIG. 6 — EXAMPLES OF NON-WETTING PHASE RELATIVE PERMEABILITY.

Curve A — Described empirically by Hassler[1] as

$$k_{rn} = e^{-7.75\rho_w^{2.25}}$$

Curve B — Eq. (23) with limiting saturation parameters chosen to fit Curve A.

Curve C — Martinelli et al data [27].

Curve D — Eq. (23) with limiting saturation parameters chosen to fit Curve C.

Curve E — A generalized solution of Eq. (10a) as applied to a non-wetting phase.

Curve F — A generalized solution of Eq. (10a) as applied to a wetting phase.

† Brownell and Katz (loc. cit.) suggest that the wetting phase removed from flow is proportional to the non-wetting phase saturation, which evidently is not in accord with the data of Russell *et al*[30] where characteristics of high mobility are attributed to interstitial brines even under conditions of low saturation. In accepting herein the concept of an immobile wetting phase its magnitude will not be related to the incidental presence of the non-wetting phase, but rather to the physio-chemical rock properties responsible, for instance, for interstitial clay hydration effects, etc. In general, then:

$$0 \leqq \Psi_w \leqq \rho_{wi} \leqq \rho_{wm} < 1$$

ever, this concept of symmetry has not been derived directly through analysis of the properties of any particular system). Presumably, this assumed character of symmetry has not been emphasized in the past simply because the end-points of the wetting and non-wetting phase relative permeability curves do not in general originate from comparables positions on the conventional data plot (cf. Fig. 4). Thus, whereas $k_{rw}(1)$ occurs at $\rho_w(1)$, $k_{rn}(1)$ does not occur at $\rho_n(1) = \rho_w(0)$; but rather it occurs at $\rho_n(1-\Psi_w = \rho_w(\Psi_w)$ where $\rho_w(\Psi_w)$ only occasionally equals $\rho_w(0)$. In a like manner, $k_{rw}(0)$ occurs at $\rho_w(\rho_{wm})$ although $k_{rn}(0)$ occurs at $\rho_n(\rho_{nm})$, where ρ_{wm} usually is considerably larger than ρ_{nm}.‡

In this connection it is observed that ρ_{wm} and ρ_{nm} are both limiting saturation parameters associated with saturation distribution conditions of the respective phases such that an infinitesimal decrease in either ρ_w or ρ_n beyond ρ_{wm} or ρ_{nm} would result in a phase discontinuity. ρ_{wm} then represents the end point of a displacement experiment where the non-wetting phase reduces the wetting phase to a minimum. (In a capillary pressure experiment $\rho_{wm} = \rho_{wi}$). Likewise, ρ_{nm} represents the end point when the non-wetting phase is reduced to a minimum. Referring to the generalized pressure-saturation diagrams in Fig. 4 it is noted ρ_{nm} is approached in a more abrupt manner than is ρ_{wm}. That is to say a funicular chord of non-wetting phase in the central pore portion of an assemblage of sand grains and surrounded by wetting phase will be abruptly pinched-off as globules by the wetting phase and thereby rendered immobile as ρ_n is decreased to ρ_{nm}. On the other hand, as ρ_w is decreased to ρ_{wm} (or ρ_{wi}) the wetting phase adhering to the pore wells is more gradually forced into a strictly pendular configuration, and, assuming 0° contact angle, actually never does become entirely discontinuous although it may so behave from a flow standpoint. In any event, there is reason to expect in the region of low phase saturation a departure from wetting and non-wetting phase symmetry in the respective relative permeability curves (that is, assuming as has been done above that a general character of symmetry does exist at other levels of saturation) which manifests itself in the form of a sharp non-wetting phase relative permeability cut-off in contrast to a more gradual wetting phase relative permeability cut-off. This then introduces a minor limitation into the unqualified use of Eq. (23) for non-wetting phase relative permeability, the quantitative magnitude which is suggested by observing the conformance between theory and experiment as presented in Fig. 5c and Fig. 6. Presumably, the theoretical relationship for wetting phase relative permeability (Eq. 22) does not invoke this limitation since it was developed from basic concepts to apply exactly to wetting phase flow in contrast to the intuitive development of the non-wetting phase relation (Eq. 23).

‡ It will be noted that Eq. (10a) appears to contradict the intuitively developed concept of inherent symmetry, as suggested by Curves E and F of Fig. 6. Indeed, all attempts at theoretical analysis of non-wetting phase relative permeability have lead to monotonic curves concave downward (as opposed to the concave upward wetting phase relative permeability curves) when plotted as in the conventional diagram (c.f. Fig. 6). In view of the conformance obtained between non-wetting phase relative permeability curves of this type and the experimental data of Botset, as illustrated by Curve E of Fig. 5, the concept of inherent symmetry should be accepted for the present only to the extent that it is useful for approximation purposes. For it is believed that in some respects at least more exacting experimentation and more rigorous theoretical development are yet to be accomplished before non-wetting phase relative permeability phenomena are completely understood.

In connection with the application of the developments presented in this paper to the three-phase flow problem some quantitative statements now can be made, again based on the concept of inherent symmetry. In the first place the evaluation of the relative permeability of a wetting phase in the presence of one or more non-wetting phases has already been accomplished to the extent that the equivalence of wetting phase relations for a given porous body is established by existing data to be independent of fluid properties (c.f. Eq. 21-5). The relative permeability to oil in a o-b-g 3-phase system has been described by Eqs. (21-3) and (21-6). In order to explain these experimental observations, one is inclined to observe with Leverett and Lewis[24] that starting with a gas-oil system and holding ρ_o constant, the oil changes its distribution by migrating from smaller to larger pores as some of the non-wetting gas is replaced by water. However, to say that this in itself tends to increase the oil relative permeability (as apparently observed) invalidates the argument presented above which lead to the concept of symmetry. That is to say, granted the average pore radius of the oil saturated portion of the system is increased as some of the gas is replaced by water, still the number of pores containing the oil is decreased simultaneously, such that it is assumed for the present that the resultant of these effects does not entirely (if at all) account for the observed facts expressed by the inequalities (21-3) and (21-6). Instead, the problem is simply solved by applying Eq. (22) when the oil acts as a wetting phase, to give the relative permeability of oil in an o-g system; and applying Eq. (23) when the oil acts as a non-wetting phase to give the relative permeability of oil in an oil-brine system. This has been done for a typical case as illustrated by the dotted lines in Fig. 2, and it is seen that the form of the inequality (21-3) should be changed by this argument to:

$$\underset{\text{o-b system}}{k_{ro}(\rho_o)} > \underset{\text{o-b-g system}}{k_{ro}(\rho_o)} > \underset{\text{o-g system}}{k_{ro}(\rho_o)}$$

since ρ_{wm} was chosen greater than ρ_{nm} according to the general case. Although indicating the relative permeability to oil in the three-phase system as immediate between that obtaining in oil-brine and oil-gas two-phase systems represents a departure from the Leverett and Lewis data (loc. cit.) intuitively it is a necessity since there has not appeared an argument which requires

$$\underset{\text{o-b-g system}}{k_{ro}(\rho_o)} \text{ to sometimes be greater than } \underset{\text{o-b system}}{k_{ro}(\rho_o)} \quad \S$$

Thus, combining Eq. (22) and (23) in a manner suggested by the above discussion we obtain as an expression for oil

§ In a like manner Fig. 2 has been prepared to indicate that Eq. (21-2) should be modified as:

$$\underset{\text{g-o system}}{k_{rg}(\rho_g)} = \underset{\text{g-b system}}{k_{rg}(\rho_g)} = \underset{\text{g-o-b system}}{k_{rg}(\rho_g)}$$

Again, although this departs from the usual interpretation of the Leverett and Lewis data no argument is apparent which supports the observation that the gas non-wetting phase relative permeability relation should be different in three-phase systems than in two-phase systems. This latter would imply the gas *knows* the nature of the wetting phase(s) simultaneously saturating the porous system, which according to the concepts assumed or established in this paper would be true only in unsteady state flow. These arguments suggest that Eq. (21-6) should be modified as:

$$\underset{\text{2-3 phase systems}}{k_{rn}(\rho_n)} > \underset{\text{o-g-b system}}{k_{ro}(\rho_o)} > \underset{\text{2-3 phase systems}}{k_{rw}(\rho_w)}$$

which is herein accepted as a qualitative description of the manner in which wetting and non-wetting phase relatvie permeabilities compare with each other in a given porous medium under the indicated conditions of equivalent phase saturation. It is apparent that this modified form of Eq. (21-6) will hold only when $\rho_{wm} > \rho_{nm}$ and/or when $\Psi_w > 0$.

relative permeability in the presence of both brine and gas:

$$\frac{k_{ro}(\rho_o)}{\text{o-g-b system}} = \frac{x}{y^2 z^2} \quad . \quad . \quad . \quad . \quad . \quad (24)^*$$

$$x = 256\rho_o^2\ (\rho_o - \rho_{om})^3\ (1 - \rho_{bi} - \rho_{om})\ (1 - \rho_{bi})^2\ (1 - \rho_{bi} - \rho_{gm})^3\ (1 - \Psi_w - \rho_{gm})$$

$$y = 2\rho_o^2\ (2 - 2\rho_{bi} - 3\rho_{om}) + 3\rho_o\rho_{om}\ (3\rho_{om} + 2\rho_{bi} - 2) + \rho_{om}(1 - \rho_{bi})\ (4 - 4\rho_{bi} - 5\rho_{om})$$

$$z = 2(1 - \rho_{bi})^2\ (2 - 2\psi_w - 3\rho_{gm}) + 3\rho_{gm}(1 - \rho_{bi})\ (3\rho_{gm} + 2\psi_w - 2) + \rho_{gm}(1 - \psi_w)\ (4 - 4\psi_w - 5\rho_{gm})$$

and where we may specifically identify ρ_{bi} as the irreducible connate water, ρ_{gm} as the equilibrium gas saturation, and ρ_{om} as the minimum oil saturation resulting from a gas drive. Fig. 7 shows how oil relative permeability varies with connate water saturation as predicted by Eq. (24), this plot being somewhat of the form suggested by the cited data of Leverett and Lewis (c.f. Fig. 9 of their paper, loc. cit.) It is concluded then that Eq. (24) can be useful to calculate oil relative permeability in three phase systems, for instance, when only two-phase laboratory data are available for study or when assumptions can be made regarding the magnitude of the various limiting saturation parameters contained in Eq. (24).

To conclude, and in order to show the usefulness of the concepts developed in this paper for the solution of problems of practical importance, the following example is given. Gas-oil ratios, which in the past have been obtained either directly from the field data or indirectly from laboratory flow tests through a knowledge of the gas-oil relative permeability ratio are required in the study of certain problems of petroleum production. From a combination of Eq. (23) (applying to gas as a non-wetting phase) and Eq. (22) or Eq. (24) (applying to oil as a wetting phase with respect to gas) one obtains a k_{rg}/k_{ro} ratio which can be generalized and approximately described by:

$$\frac{k_{rg}}{k_{ro}} = \left[\frac{(1 - \rho_o - \rho_{bi} - \rho_{gm})\ (1 - \rho_{bi} - \rho_{om})\ (1 - \psi_w - \rho_{gm})}{(1 - \rho_{bi} - \rho_{gm})\ (\rho_o - \rho_{om})\ (1 - \rho_{gm})}\right]^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (25)\dagger$$

where:

$$\rho_o + \rho_g + \rho_{bi} = 1$$

Here again, ρ_{bi} represents the connate water, ρ_{gm} represents the equilibrium gas saturation, and ρ_{om} is the non-producible oil saturation by gas drive as was obtained for instance in the experiments of Holmgren (loc. cit.).

* Thus, Eq. (24) reduces to Eq. (22) when $\rho_{bi} = 0$ and the oil acts as a wetting phase; and Eq. (24) reduces to Eq. (23) when $\rho_g = 0$ and the oil acts as a non-weting phase. When all three phases (oil, gas and connate water) are present Eq. (24) implies that the oil is acting as a wetting phase with respect to gas in the pore spaces left when the connate water is considered as a part of the confining matrix along with the solid phase. This would seem to indicate that Eq. (24) should not be employed to predict the oil relative permeability when unreasonably high values are assumed for the connate water term, ρ_{bi}.

† More exact evaluation of this ratio entails appropriately solving Eqs. (20), (22), (23), and/or (24) as required by the conditions under consideration.

Fig. 8 shows a plot Eq. (25) as it compares with cited data,‡ and again fair conformance is noted, suggesting the applic-

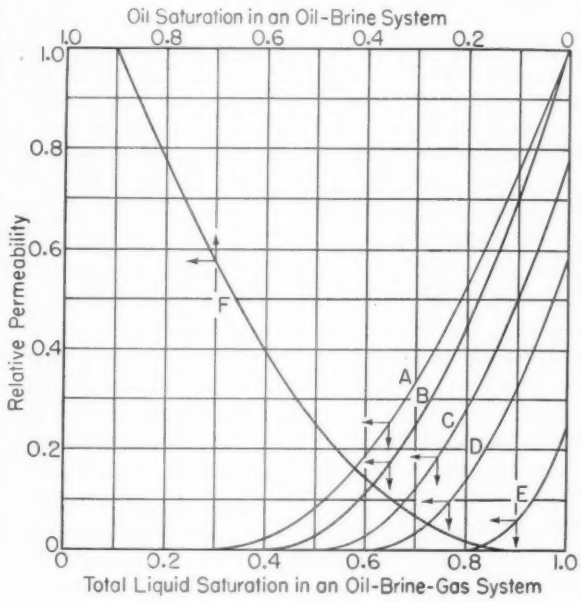

FIG. 7 — EFFECT OF CONNATE WATER ON THE OIL RELATIVE PERMEABILITY RELATION.

Curve A — Oil relative permeability in an oil-gas system containing no connate water (viz. Eq. (22)).

Curves B, C, D and E — Oil relative permeability in oil-gas-brine systems where ρ_{bi} is assumed to be 0.1, 0.2, 0.3 and 0.5 respectively and where ψ_w is assumed to be 0.1 in each case. (viz. Eq. (24)).
Curve F — Oil relative permeability in an oil-brine system. (viz. Eq. (23)).

‡ For example, in setting up Eq. (25) to describe a typical three-phase case the following assumptions were made:

$$\psi_w = 0.1;\ \rho_{gm} = 0.1;\ \rho_{om} = 0.3,$$

and,

$$\rho_{bi} = 0,\ 0.1,\ 0.2 \text{ and } 0.4$$

for the four examples given, yielding curves which can be compared directly to the relations illustrated in Fig. 7. Eq. (25) is rewritten as:

$$\frac{k_{rg}}{k_{rw}} = \left[\frac{(1 - \rho_w - \rho_{gm})\ (1 - \rho_{wm})}{(1 - \psi_w - \rho_{gm})\ (\rho_w - \rho_{wm})}\right]^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (25a)$$

when it is desired to describe approximately two-phase experimental data. Therefore, in setting up Eq. (25a) to fit Botset's[3] data

$$\psi_w = 0.35,\ \rho_{gm} = 0.1 \text{ and } \rho_{wm} = 0.5$$

were assumed as suggested by Fig. 5.

ability of the concepts presented in this paper at least for engineering use. Thus, it is seen that by Eq. (25):

$$\lim_{\rho_g \to \rho_{gm}} \frac{k_{rg}}{k_{ro}} = 0$$

and,

$$\lim_{\rho_o \to \rho_{om}} \frac{k_{rg}}{k_{ro}} = 00$$

in accord with accepted concepts. Further, it is noted increasing ρ_{b1}, or increasing ρ_{om}, or decreasing ρ_{gm}, in each case holding the other limiting saturation parameters constant, will tend to increase the k_{rg}/k_{ro} ratio at a given total liquid saturation.

SUMMARY AND CONCLUSIONS

To summarize, this paper has treated the subject of calculated relative permeability according to the point of view that the configuration of the saturating fluid phases alone determines the relationships which will prevail in steady state flow. Specifically an expression for wetting phase relative permeability has been derived from fundamental considerations based on modified forms of the Kozeny equation for flow and Leverett's expression for capillary retention. Although the derivation presented is neither rigorous nor unique it is supported through the indicated conformance of predicted results with existing experimental data. Then, postulating the concept of inherent symmetry as a character interrelating wetting and non-wetting phase relative permeability relationships the limiting saturation parameters

$$\lim_{k_r \to 1} \rho \quad \text{and} \quad \lim_{k_r \to 0} \rho$$

have been defined. This in turn has led to an expression for non-wetting phase relative permeability which again is supported by conformance to existing data. Finally, general consideration has been given to the problems of three-phase relative permeability phenomena and gas-oil ratios.

In view of the considerations which have been examined in this paper it is concluded that the pore widths of the interstitial spaces in contact with the immiscible fluid phase interfaces saturating these spaces is the factor of importance in controlling the effective permeability of the porous body to these phases. Essentially, capillary pressure data identifys the distribution of pore widths with a range of fluid phase saturation configurations under conditions of static equilibrium, and it is shown herein how this fact can be employed to derive a generalized expression for the relative permeability relation explicitly defined in terms of saturation parameters. In suggesting that the effective permeability characteristics in polyphase systems are controlled by the magnitude of the pore spaces available for flow under the prevailing conditions of saturation distribution, it is recognized that the limiting saturations where phase discontinuities occur also have an importance in defining the detailed features of the observed relations. Moreover, it has been suggested that in a given porous body the conditions of flow determine the effective distribution of pore widths associated with the prevailing saturation configurations as well as determine the exact occurence of the phase discontinuities. Therefore, hysteresis effects analogous to those observed in static capillarity studies are to be anticipated as observable phenomena in relative permeability work. In this connection, the generalized expressions for relative permeability presented in this paper presumabily can be used to calculate the various limits of hysteresis through suitable selection of the saturation parameters, although experimental proof is nonetheless desired to further establish the validity of the assumptions which have lead to these expressions. Finally, it is concluded that insofar as confirmation is offered by available data a character of symmetry seems to interrelate wetting and non-wetting phase relative permeability relations in a manner requiring only the knowledge of the above mentioned limiting saturation param-

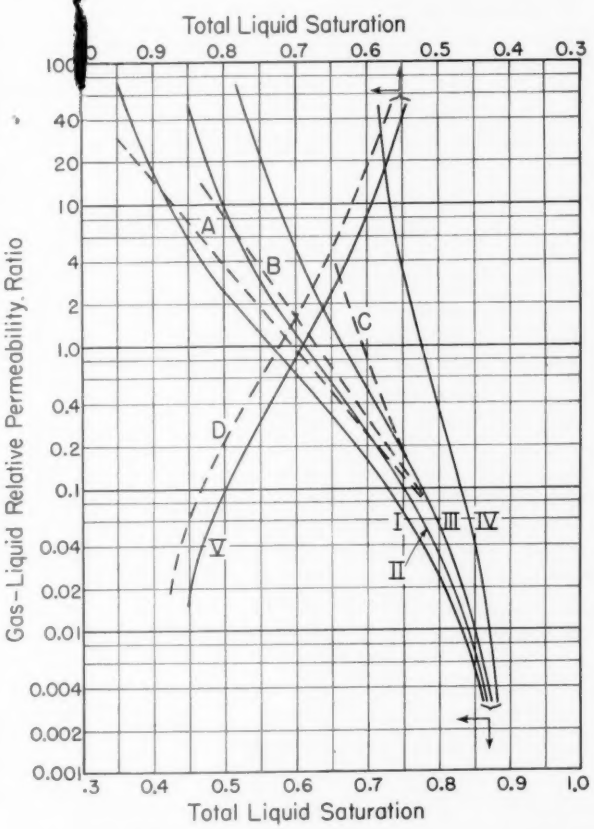

FIG. 8 — RELATION OF GAS-LIQUID RELATIVE PERMEABILITY RATIO TO TOTAL LIQUID SATURATION.

Curves A, B and C gas-oil ratio data of Leverett and Lewis[24] where $\rho_{b1} = 0$, 0.2 and 0.4 respectively.

Curves I, II, III and IV — Eq. (25) with limiting saturation parameters chosen to approximately describe the Leverett and Lewis data, and where $\rho_{b1} = 0$, 0.1, 0.2 and 0.4 respectively.

Curve D — Data of Botset[3].

Curve V — Eq. (25a) with limiting saturation parameters chosen to approximately describe Curve D.

eters in order to treat the various problems of steady state polyphase flow.

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NOMENCLATURE

(1) *Permeability Terms*

- k — specific permeability
- k_e — effective permeability
- k_r — relative permeability (fractional)

(2) *Saturation Terms* (all per unit of pore volume expressed as fractions)

- ρ — fluid saturation
- ρ_i — limiting minimum saturation attained in static capillary pressure experiment
- ρ_m — limiting minimum saturation attained in dynamic flow experiment
- ψ_w — immobile wetting phase saturation

(3) *Rock and Fluid Property Terms*

- A — specific surface area of pores per unit of pore volume
- f — porosity (fractional)
- t — Kozeny Rock textural constant
- T — collective term for Rock Textural Properties
- μ — fluid phase viscosity
- σ — interfacial tension
- P_c — capillary pressure
- P_D — displacement pressure
- π_c — dynamic equivalent of P_c
- π_D — dynamic equivalent of P_D
- $j(\rho_w)$ — capillary pressure function (wetting phase)
- dp/dx — pressure gradient in the x-direction
- q — linear rate of fluid flow
- D_r^- — distribution coefficient of pore radii
- r — pore radius
- θ — contact angle

(4) *Miscellaneous Symbols*

- F — denotes functional relationship
- G — acceleration due to gravity
- $\Phi(\rho_w)$ — Rho Function

(5) *Subscripts*

- w — refers to a wetting phase (unspecified)
- n — refers to a non-wetting phase (unspecified)
- b — refers to a brine (aquous) phase
- o — refers to an oil phase
- g — refers to a gas phase
- e — denotes *effective*
- r — denotes *relative*
- m — refers to minimum saturation value attained under dynamic flow conditions
- i — refers to minimum saturation value attained in a static capillary pressure experiment.

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DISCUSSION

By A. C. Bulnes, Shell Oil Co., Midland, Texas

Walter Rose is to be congratulated on an excellent paper and one which constitutes, in my opinion, a most important contribution to the subject of polyphase flow in porous media.

Particularly gratifying is the fact that it has been found possible to develop a comparatively simple expression for relative permeability from the fundamentals of capillary phenomena and the quantitative measures of rock properties, together with the aid of certain rather generous assumptions, instead of being forced to fall back upon some unobvious and complicated empirical result. Moreover, in the process of this derivation, the relationship existing between the measured data of relative permeability, capillarity, and the void structure of the medium is also brought out in a clear and simple fashion and should be of interest to many readers.

The relative permeability of the wetting phase is shown to be a function of ρ_w and of an irreducible saturation ρ_{wm} or ρ_{wi}. The determination of ρ_{wi} is relatively simple, or at any rate, it is easy to describe an experiment whereby it can be measured. This does not appear to be the case for ρ_{wm}; in fact, it is not clear to me just how this quantity can be determined except in terms of the relative permeability; that is, by solving it in Eq. (22), a procedure that would defeat the purpose for which this equation was developed. Moreover, although it appears reasonable to conclude that ρ_{wi} is a lithologic property independent of the fluid properties, it is not evident that the same statement can be made as regards ρ_{wm}. I would appreciate the comments of the author on the foregoing observations.

The assumption that $t_{ew} = t$ is of considerable importance in the mathematical developments and may be accepted as a reasonable first approximation. Rose indicates that if not equal to t, t_{ew} is some function of the saturation. I would like to ask Rose if he considers that t_{ew} may be also a function of the interfacial tension, in which case we would expect the relative permeability to display a dependence upon this quantity. Granting the inequality of t_{ew} and t, I wonder whether Rose would care to express an opinion as to the range of variation to be anticipated in t/t_{ew} for normal variation in ρ_w and/or σ, and also whether abandonment of the assumption of unity as the value of the textural constant ratio would lead to fundamental changes in the shapes of the theoretical curves in Fig. 3.

☆

Author's reply to A. C. Bulnes

Upon reflection I find that my paper is an admixture of theoretical probabilities and theoretical possibilities. The latter are not to be too seriously considered, although perhaps it might be said they stimulate interesting argument. On the other hand the probabilities are believed to be of some importance, and Bulnes has cleverly focused attention on this importance by questioning a major assumption upon which the theoretical developments are based. In view of the fact that no one heretofore has dealt with the textural characterization of polyphase saturated porous media it is appropriate

therefore to set forth the rationale of the concept that the ratio, t/t_{ew}, is reasonably constant throughout the saturation interval of interest. This is best done by recalling that the textural factor is defined as the product of a pore shape factor and a pore tortuosity factor. There appears to be no reason to attempt to describe the variation of shape factors with fluid saturation since it is well established in the literature that these generally fall within the narrow range of 2.0 to 2.5, as applied to homogeneous fluid saturated media, and by implication at least as also applied to polyphase saturated porous media.§ On the other hand, the tortuosity factor cannot be so easily disposed of as an universal constant, for values are found to range between 2 and over 200 for consolidated porous media. (A tortuosity value close to 2 is usually quoted for unconsolidated porous media of various particle size, shape and surface characters). Therefore, perhaps we should expect that as the "equilibrium" saturation of the non-wetting fluid is developed, the tourtuosity factor will increase since a given element of flowing wetting liquid will have to pass around additional barriers of non-wetting fluid in the central pore spaces. However, it is suspected that once the equilibrium saturation of the non-wetting fluid is established, the tortuosity factor thereafter will remain sensibly constant at all other wetting liquid saturation levels above the minimum where the wetting liquid itself becomes discontinuous. This is because the tortuosity factor is a dimensionless ratio of actual length of fluid streamline to apparent length (i.e. actual bed length). By representing the non-wetting fluid saturation as interconnected spheres located in the central pore spaces it is seen that the ratio will be independent of the distribution of spheres (i.e. the non-wetting fluid saturation) as an approximation.

Thus, whereas t/t_{ew} has been assumed equal to unity in the paper, it would appear that the ratio actually tends to decrease initially as continuity in the non-wetting fluid is being established, thereafter remaining nearly constant and less than unity throughout the wetting liquid saturation interval of interest. Although this conclusion is based on highly speculative argument it is noted that better conformance between Curve D of Fig. 5 in the paper and the associated experimental data follows if the above described variation of the t/t_{ew} ratio is employed in the solution of Equation 10. Actually, however, it appears that the development followed in the paper (based on the Rho function concepts) obviates the necessity of giving explicit treatment to the rock textural factors, for the analytical expressions finally developed to describe relative permeability phenomena give good conformance between theory and experiment. In any event, it will be clear from the definition of the texture factor that the term, t_{ew}, does not depend directly on fluid properties such as interfacial tension. In this respect, perhaps Bulnes implies that the dynamics of a given system might result in a dependence of the fluid distribution on such fluid properties, which conceivably could result in a dependence of tortuosity (and therefore texture) factors on fluid properties since tortuosity certainly must depend on fluid distribution character. Such dependence, however, will not be easily evaluated. Indeed, it may be regarded that an object of the writer's paper has been to present the view that the characters of polyphase flow through porous media are (a) inadequately understood, and (b) difficult to evaluate either experimentally or theoretically. This condition, sadly enough, permits theorists to say almost anything and empiricists to report almost any data without immediate fear of serious contradiction.

To reply to the comments of Bulnes about the difficulty of evaluating the term, ρ_{wm}, appearing in Eq. (22) of the paper, further reference is made to the correlation of Brownell and Katz as cited in the paper footnote following Eq. (22).* The qualitative correctness of the form of this correlation has been supported recently by the examination of certain unpublished data obtained at this laboratory. It is believed therefore that controlled flooding experimentation should serve adequately for the determination of the limiting saturation parameters such as ρ_{wm} and ρ_{nm}. In any event, the feeling expressed by Bulnes that these limiting parameters will be dependent on fluid properties is born out by the cited result due to Brownell and Katz. ★ ★ ★

§ See for example the recent Carman paper (*Discussions of the Faraday Society*, No. 3, 72-77, 1948), discussing these considerations.

* In the preprint version of the paper the Brownell-Katz equation for ρ_{wm} was incorrectly given.

EVALUATION OF CAPILLARY CHARACTER IN PETROLEUM RESERVOIR ROCK

WALTER ROSE, JUNIOR MEMBER AIME, GULF RESEARCH & DEVELOPMENT CO., PITTSBURGH, PA.
W. A. BRUCE, MEMBER AIME, THE CARTER OIL CO. RESEARCH LABORATORY, TULSA, OKLAHOMA

ABSTRACT

Improved apparatus, methods, and experimental techniques for determining the capillary pressure-saturation relation are described in detail. In this connection a new multi-core procedure has been developed which simplifies the experimental work in the study of relatively homogeneous reservoirs. The basic theory concerning the Leverett capillary pressure function has been extended and has been given some practical application. Some discussion is presented to indicate the relationship of relative permeability to capillary pressure, and to provide a new description of capillary pressure phenomena by introducing the concept of the psi function.

INTRODUCTION

For the purposes of this paper the capillary character of a porous medium will be defined to express the basic properties of the system, which produce observed results of fluid behavior. These basic properties may be classified in the following manner, according to their relationship to:

(a) *The geometrical configuration of the interstitial spaces.*

This involves consideration of the packing of the particles, producing points of grain contact, and variations in pore size distribution. The packing itself is often modified by the secondary processes of mineralization which introduces factors of cementation, and of solution action which causes alteration of pore structure.

(b) *The physical and chemical nature of the interstitial surfaces.*

This involves consideration of the presence of interstitial clay coatings, the existence of non-uniform wetting surfaces; or, more generally, a consideration of the tendency towards variable interaction between the interstitial surfaces and the fluid phases saturating the interstitial spaces.

(c) *The physical and chemical properties of the fluid phases in contact with the interstitial surfaces.*

This involves consideration of the factors of surface, interfacial and adhesion tensions; contact angles; viscosity; density difference between immiscible fluid phases; and other fluid properties.

Fine grained, granular, porous materials such as found in petroleum reservoir rock possess characteristics which are expressible by (1) permeability, (2) porosity, and (3) the capillary pressure-saturation behavior of immiscible fluids in this medium. These three measurable macroscopic properties depend upon the microscopic properties enumerated above in a manner which defines the capillary character.

Systems of capillary tubes or regularly packed spheres may be thought of as ideal and numerous references can be cited in which exact mathematical formulations are developed to show the relationships governing the static distribution and dynamic motion of fluids in their interstitial spaces. The capillary character of non-ideal porous systems such as reservoir rock also is basic in determining the behavior of fluids contained therein; although, in general, the connection is not mathematically derivable but must be approached through indirect experimental measurement. This paper gives consideration to the evaluation of petroleum reservoir rock capillary character. The methods employed may be applied to the solution of problems in other fields, and the conclusions reached should contribute to the basic capillary theory of any porous system containing fluid phases.

In this paper, a modification of the core analysis method of capillary pressure is employed and it is intended to show that the capillary character of reservoir rock can be expressed in terms of experimental quantities. A very general method of interpretation correlating the capillary pressure tests with fundamental characteristics such as rock texture, surface areas, permeability, occasionally clay content and cementation is introduced. Eventually an attempt is made for establishing a method of deriving relative permeability to the wetting phase from capillary pressure data.

The experimental evaluation of capillary character must be approached in a statistical manner if reservoir properties are to be inferred from data on small cores. This is implied by the heterogeneous character of most petroleum reservoirs, and suggests that considerable intelligence should be applied in core sampling. Finally, this paper supports the view that once the capillary character of a given type of reservoir rock has been established by core analysis, fluid behavior can then be inferred in other similar rock. Although no great progress has been made in establishing what variation can be tolerated without altering the basic fluid behavior properties, evidence will be presented to indicate that certain reservoir formations are sufficiently homogenous with respect to capillary character that the data obtained on one core will be useful in predicting the properties of other cores of similar origin. Tests have shown that cores under consideration can vary widely with respect to porosity and permeability and still be considered similar in capillary character.

EXPERIMENTAL METHODS AND TECHNIQUES

Various types of displacement cell apparatus for capillary pressure experiments have been described in the literature. Bruce and Welge[1]; Thornton and Marshall[2]; McCullough, Albaugh and Jones[3]; Hassler and Brunner[4]; Lever-

Manuscript received at Petroleum Branch Office August 31, 1949.
[1] References are given at end of paper.

ett[9]; and others have used various types of apparatus to measure the interstitial water in petroleum reservoir cores. Richards[6] developed a similar apparatus to study soil sorption, and he gives references to the work and apparatus of ten previous experimenters in this field of soil physics. Of particular interest is the early work of Haines[7,8] in which he describes methods of studying capillary pressure hysteresis effects, and the work of Leamer and Lutz[9] in which they propose and use displacement cells to evaluate pore size distribution in porous systems. More recently Welge[10] has described displacement apparatus to measure oil displacement, and Amyx and Yuster[11] have described apparatus which they are using in their secondary recovery study.

None of the conventional techniques referred to above are entirely suited to the purposes of the experimental program reviewed in this paper. This was due in part to the desire to develop multiple-core techniques; and also to the fact that conventional apparatus was characterized by (a) the limited range of temperature and pressure conditions which could be employed in experiments using the apparatus, (b) the complicated assembly and cleaning features which made experimental work tedious, and (c) by the semi-permeable barrier failure trouble which introduced apparatus errors into the experimental results. The modified apparatus described below was designed to overcome these limitations, and also to make the rapid accumulation of the experimental data discussed in this paper. It is of interest to mention here that Richards[6,12,13,14,15] working in a different field (soil science) anticipated many of the requirements which should be incorporated into displacement cell design to satisfy the purposes of petroleum reservoir behavior study, and his pioneering work has contributed to some of the developments reported here.

A displacement cell should be regarded as a reservoir model system wherein the conditions which produce effects in the reservoir can be simulated adequately in a laboratory experiment. Fig. 1 shows how basic parts of the apparatus illustrated in Figs. 2 and 3 can be assembled in a variety of ways when various types of experiments are contemplated. It can be supposed that the core element represents some volume portion of the reservoir under consideration. This core may be saturated with fluid phases according to the saturation condition of the represented portion of the reservoir at some initial state. Surrounding the core in a high pressure chamber is an environment of the displacing fluid phase. The core itself is placed in capillary contact with a semipermeable barrier which is preferentially wetted by, permeable to, and saturated with the immiscible fluid phase to be displaced from the core. Thus, this membrane barrier separates the high pressure chamber containing the core and filled with the displacing phase from a low pressure chamber filled with the phase to be displaced. The establishment of a suitable pressure difference across the membrane barrier, in general, causes the displacing phase to enter some interstitial portions of the core producing a displacement of the wetting fluid from the system.

This reservoir model system permits a quantitative measurement of the character of the displacement which is caused by the pressured advance of the displacing phase into the interstitial spaces, and which results in the displacement of the fluid originally occupying these spaces. The experimental data which can be obtained yield relationships involving capillary pressure, fluid saturation and rates of displacement.

The means for interchange of the semipermeable barrier is a special feature of the displacement cells illustrated in Figs. 2 and 3. This is desired particularly when changing from aqueous phase displacement to oil phase displacement since no single barrier can serve both of these purposes. Inter-

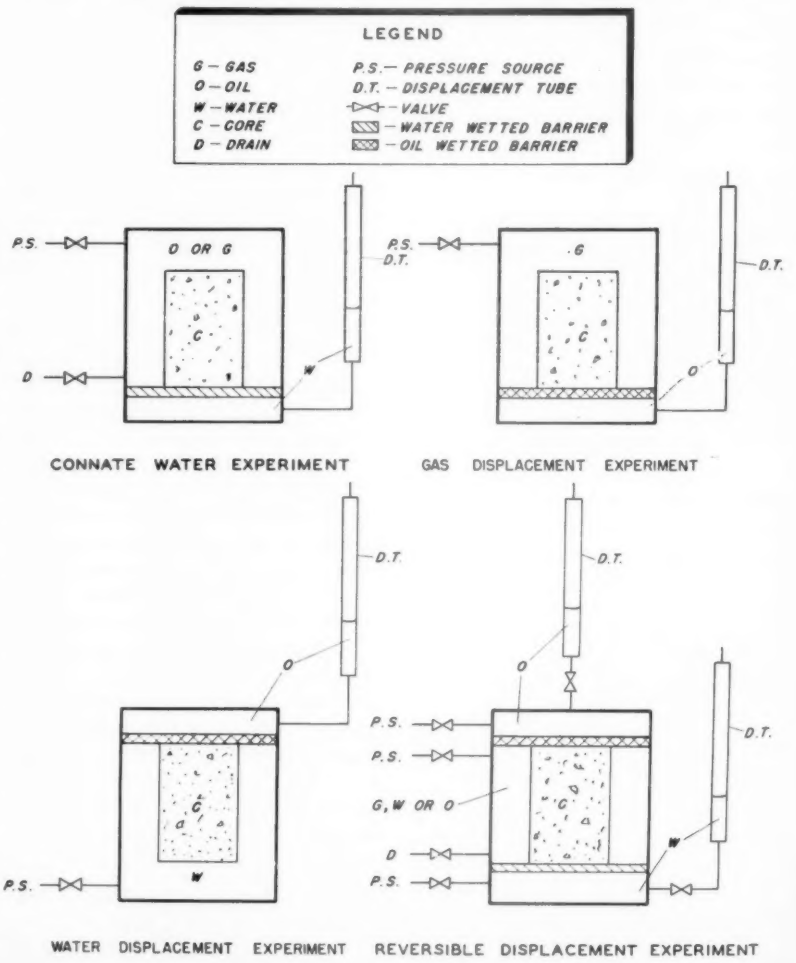


FIG. 1 — DISPLACEMENT CELL ASSEMBLIES.

changeability is also desired when changing from low to high capillary pressure operations, and when changing from one operation to another of the same type, additional barriers being required because of prior failure or similar reason. These considerations can be clarified by describing the necessary properties which characterize semipermeable barrier material. In the first place the barrier must have surface characteristics such that it is preferentially wetted by the phase to be displaced from the cores when it is saturated with this phase. This means that the nonwetting (immiscible) displacing phase cannot permeate the barrier until some critical threshold pressure is exceeded, at which time the forces of capillarity are no longer sufficient to keep the pores of the barrier saturated with the wetting phase. On the other hand, the wetting phase can permeate the barrier under any condition of pressure difference across the barrier. It is evident then, that the semi-permeable behavior of a given membrane material can be realized only when the operating conditions are confined within a definite displacement pressure range. Many materials have been considered suitable to use as semipermeable barriers in displacement cells. Among these might be listed porous ceramic and porcelain materials, cellophane and collodion type materials, sintered glass and metal, unconsolidated beds of barium sulfate and carbon, porous rubber, carbon discs, animal membranes, etc. Some of these materials are irreversibly water or oil wetted, while others can be rendered either water or oil wetted by suitable chemical treatment of the internal pore surface. The treatment of membranes to change their wetting character has been described by Welge[10] and Amyx and Yuster[11].

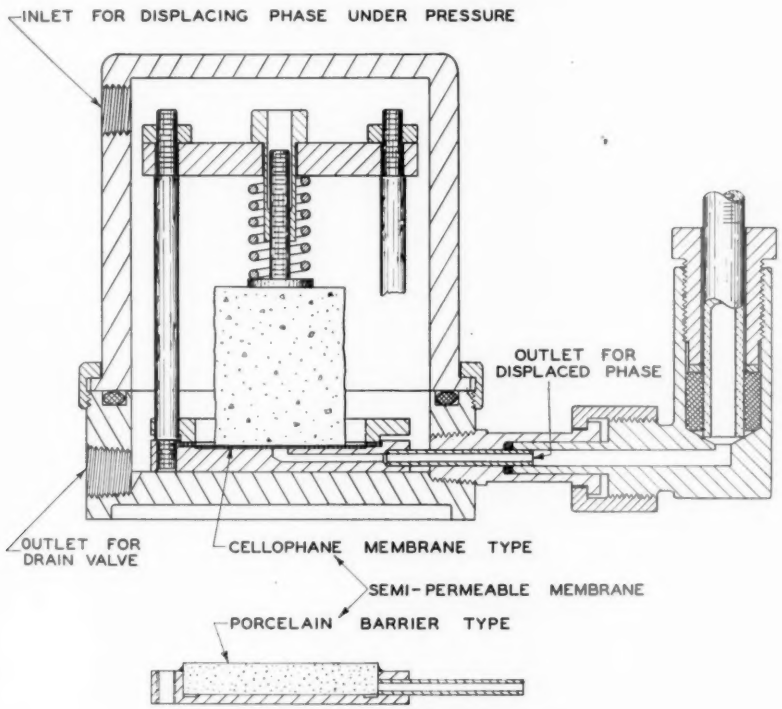


FIG. 2 — SINGLE CORE DISPLACEMENT CELL.

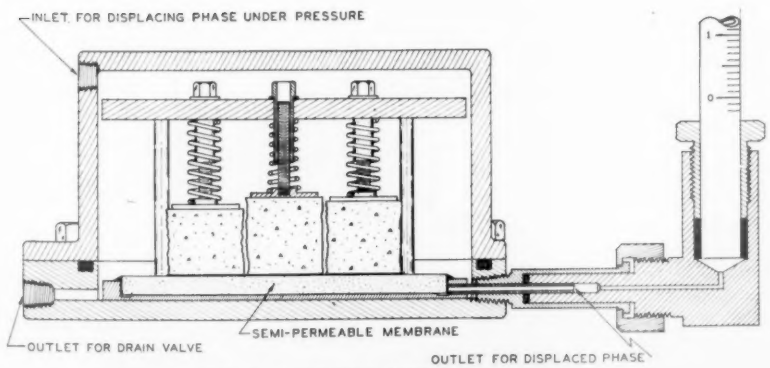


FIG. 3 — MULTI-CORE DISPLACEMENT CELL.

Fig. 2 shows that the lid and base member are joined together by a threaded coupling to form a pressure chamber. A self-sealing type gasket provides the desired pressure seal. This diagram shows how a spring mechanism holds the core element in capillary contact with a cellophane type semipermeable barrier. The membrane barrier is in turn gasketed in a holder which has a central flow channel extending downward from the surface supporting the membrane and core, and thence outward through a series of tubes, adaptors and other parts to a volumetric fluid measuring (glass) tube located on the outside of the pressure chamber. Indicated also in the diagram is a porcelain semipermeable barrier cemented in another type holder which is interchangeable with the cellophane membrane holder, and which has a similar flow channel arrangement. The cell itself has several threaded ports through which the displacing fluid can be admitted and through which fluids can be drained out, according to the requirements of the experimental procedure followed.

Referring to Fig. 3 it is seen that the multi-core cell differs from the single core cell (Fig. 2) principally in capacity and size. The illustrated apparatus will accommodate eight one-inch core plugs, although other multicore cells have been built to accommodate more than twenty cores. It is often regarded as being more desirable to analyze rapidly a number of cores for approximate values than to devote excessive time to the acurate analysis of a single core. Therefore, the multi-core displacement apparatus is particularly useful for routine work. Another object of the multi-core approach is the possibility of filling the

cell with a number of small core fragments and then, in the interpretation of the displacement data, collectively regarding these fragments as contributing to the behavior of some hypothetical core (or reservoir). This technique provides a rapid means of obtaining displacement data and a means of studying a collection of small rock fragments (e.g. cuttings) where individual analysis of any single fragment would be impractical because of the large relative error involved in accurately measuring small volumes of displaced fluid.

Several schemes have been devised to measure the degree of displacement in capillary pressure experiments. Volumetric measurement (visually or electrically) of the displacing phase entering, or the displaced phase leaving the displacement cell is a method commonly employed. Core conductivity measurements also have been employed to indicate core brine saturation. This scheme is satisfactory if sufficient care is taken to control electrode contact potentials, and if a calibration curve is available relating conductivity to saturation for the particular system being studied.

The most reliable and certain way of determining fluid saturation is by distillation and extraction. Fig. 4 shows a modified Dean-Stark apparatus which has been designed to be used according to the method of Rall and Taliaferro[16] for water and oil measurement in core samples. This apparatus differs from the Bureau of Mines apparatus[16] in ways which permit more accurate measurement of small quantities (0.1 ml. or less) of water. The vapor entry from the sample flask into the condenser tube is through the water jacket at the side so that the condensed solvent vapors are cooled as they pass the trapped water distillate in refluxing back to the sample flask. This eliminates loss of trapped water by secondary distillation out of the top of the condenser tube, and also allows ultimate recovery to be attained more rapidly. A second feature involves rendering water-repellent the entire inner glass surface of the apparatus as well as all ground glass tapered joints. This is accomplished by treatment with alkyl-chloro-silane (G. E. Dri-film).[19] After such treatment it is observed that the condensed water droplets fall freely by gravity into the water trap rather than adhere to the glass condenser surfaces. In designing the water trap a stopcock has been placed at the bottom of the calibrated tube. By filling this volume-calibrated water trap tube with mercury at the beginning of the analysis the trapped water collects in the large diameter upper portion of the trap. Withdrawal of the mercury at the end of the analysis through the stopcock draws this recovered water into the small volume-calibrated portion of the trap, and in this way smaller water values can be measured more accurately than with conventional apparatus.

THE CAPILLARY PRESSURE-SATURATION RELATION

It is a special purpose of this paper to describe apparatus, develop theory, and present data which will indicate a rapid and reliable way to measure the capillary pressure relationship and to indicate briefly the practical and theoretical importance of the data which are obtained. Experimental methods and techniques of the type described above have a wide range of usefulness in core analysis as is evidenced by the general acceptance of capillary pressure techniques to study connate water and oil production characteristics of petroleum reservoirs[1,2,3,4,5,10,11]. Although Leverett[17] and Hassler, Brunner and Deahl[18] originally emphasized the importance of evaluating the entire capillary pressure curve including the zone of hysteresis, recent authors[1,7,2] have concentrated more on the engineering applications of capillary pressure data. In this paper, the theoretical and practical importance of the entire capillary pressure curve is stressed along with the importance of certain critical portions of this curve.

The references cited attempt to show that certain types of capillary pressure study will reveal information about the saturation distribution of fluid phases which existed under some given reservoir condition. This represents a possibility only insofar as core properties are a true measure of over-all reservoir properties, which presumes a condition of homogeneity seldom encountered in petroleum reservoirs. Generally, this limitation is recognized and efforts are made to average the data statistically in a manner which permits inference of approximate fluid distribution. How-

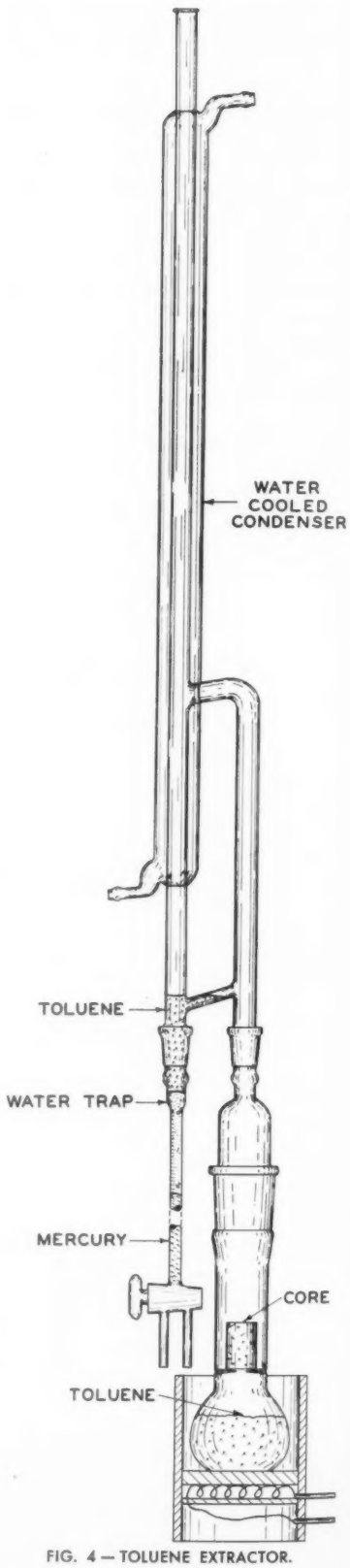


FIG. 4 — TOLUENE EXTRACTOR.

ever, another limitation must be recognized before these engineering applications of capillary pressure data will be acceptable on theoretical grounds. It has been stated that in the capillary pressure experiments an attempt is made to simulate reservoir conditions, in order to produce measurable reservoir-like effects on a core reservoir model. This requires a perfect knowledge of the reservoir processes to be simulated, and an ability to accomplish physically the desired processes. The fact that there is a marked hysteresis effect in the capillary pressure relation emphasizes this requirement. In certain instances, therefore, it may be questioned whether or not an adequate knowledge can be had regarding what occurred in the reservoir over geologic time. For instance, it is desired in capillary pressure work to attain conditions of static equilibrium only to the extent that this state prevails in the reservoir, a factor which may or may not be known. These recognized limitations present problems which will be solved eventually. Although the data and methods presented contribute to the solution of these problems, the special object of this paper is to demonstrate that capillary pressure work has another value, unlimited by the considerations which limit the engineering applications of capillary pressure data. That is, the capillary pressure curve associated with a porous system provides a characterization of the capillary properties of the system, and this is desired in the proper interpretation of observed fluid behavior in porous media.

A capillary pressure experiment is defined as a process in which a fluid phase saturating the interstices of a porous rock system is displaced by the advance of other immiscible displacing phases. This displacement is observed to continue until the displacing forces become balanced by the opposing forces of capillarity, approaching a condition of static equilibrium. Figs. 5, 6, and 7 shows a series of capillary pressure curves of the type commonly encountered. There is a finite threshold pres-

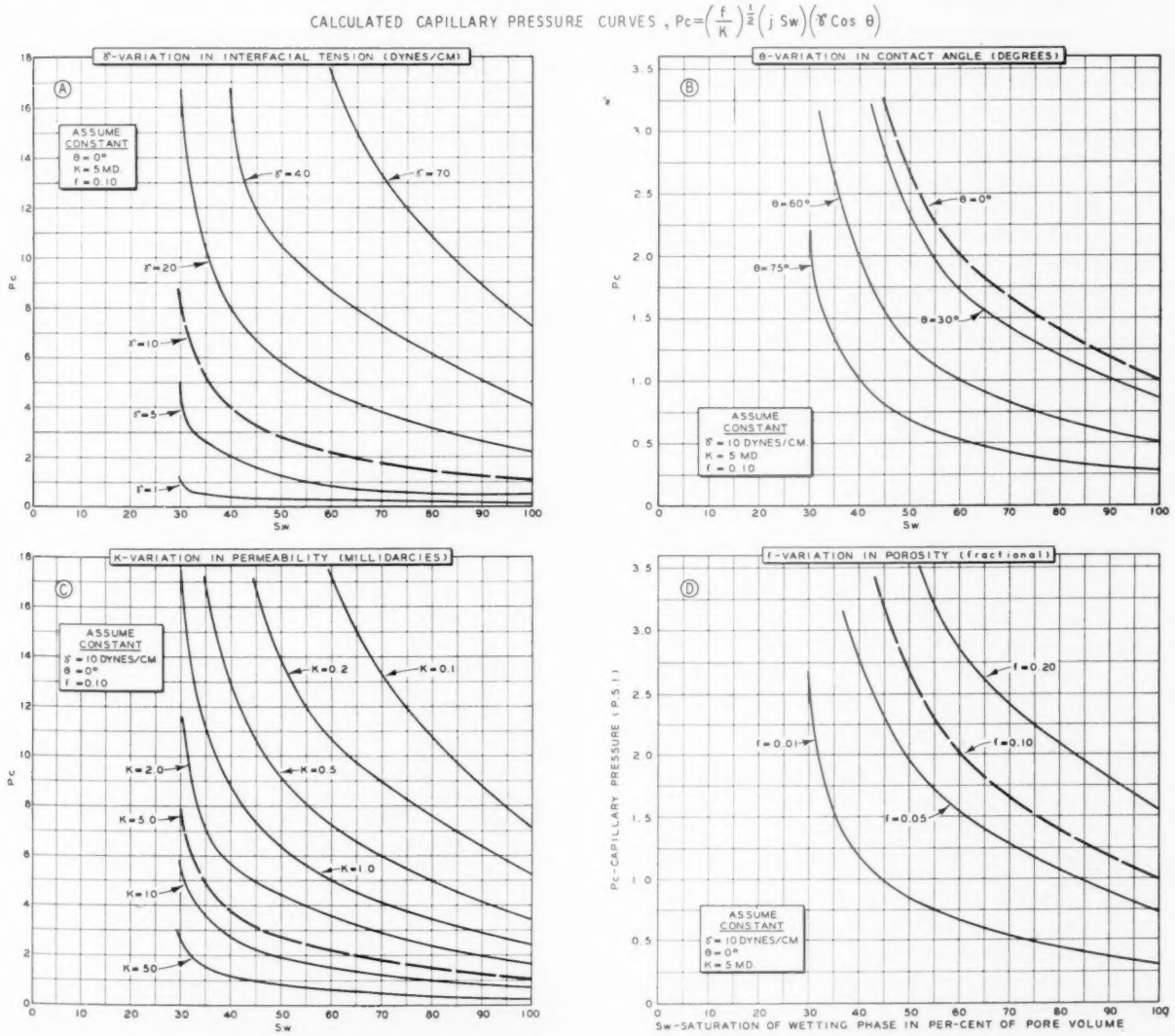


FIG. 5 — CALCULATED CAPILLARY PRESSURE CURVES, $P_c = \left(\frac{f}{K}\right)^{1/2} j(S_w)\ (\gamma \cos \theta)$

sure which must be exceeded before displacement occurs. This is followed by a near horizontal portion of the curve and then a near vertical portion which seems to indicate an asymptotic approach to some "irreducible minimum" value of the wetting phase saturation at high capillary pressures.

The concept of irreducible minimum water saturation has resulted from the nearly vertical character of the P_c vs. S_w curves. If these curves are going to approach zero wetting phase saturation at infinite capillary pressure, it is possible but not likely that a true irreducible minimum exists. For purposes of engineering work, it has been in the past assumed that a working irreducible minimum exists and can be determined experimentally. This minimum has been defined as that portion of the curve for which the saturation does not change appreciably for a fairly large change in capillary pressure. Experiments not reported here have indicated that oil as a displacing medium tends to produce a curve which becomes more definitely vertical than in the case when air is used to displace the wetting phase. Two phenomena may have a bearing on the wetting phase saturation in the region of low saturation. In the first place, conditions of wettability may be such that in the funicular saturation region water is distributed in the pores in a different manner when oil is the displacing fluid than it is when air is used. In the second place as the displacing fluid moves the water successively into smaller pores it is to be expected that some water will be trapped in the pockets from which there is no exit for fluid to move by viscous flow. If gas is the displacing fluid it is possible for the trapped water to escape by diffusion process and qualitative calculations indicate that the time for diffusion is of the order of days for 99% equilibrium. If oil is the displacing medium a pocket of water which has been trapped will require a time of the order of tens of years to move out by diffusion. While this time is long enough for equilibrium in a reservoir, it is not long enough for equilibrium in a laboratory experiment. Another way of stating this is that an irreducible minimum exists when oil displaces water and that this irreducible minimum is that saturation at which water ceases to move as a viscous fluid.

These considerations are important in the application of capillary pressure data to the study of interstitial water distribution of a virgin reservoir. It may be concluded that the use of reservoir fluids constitutes the preferred procedure in experimental work where the reservoir conditions of *low* capillary pressure are to be simulated. Under these conditions fluid properties such as interfacial tension are of importance.

On the other hand, it may be concluded that substitution of an inert gas for oil as the displacing phase may be the preferred procedure when reservoir conditions of *high* capillary pressure are to be simulated. Under these conditions, fluid properties such as interfacial tension seem to have little or no effect on the resulting wetting phase saturations as is evidenced by the near, vertical shape of the capillary pressure curve in this region.

To conclude the section on the capillary pressure-saturation relation, reference is again made to Fig. 5 to show the

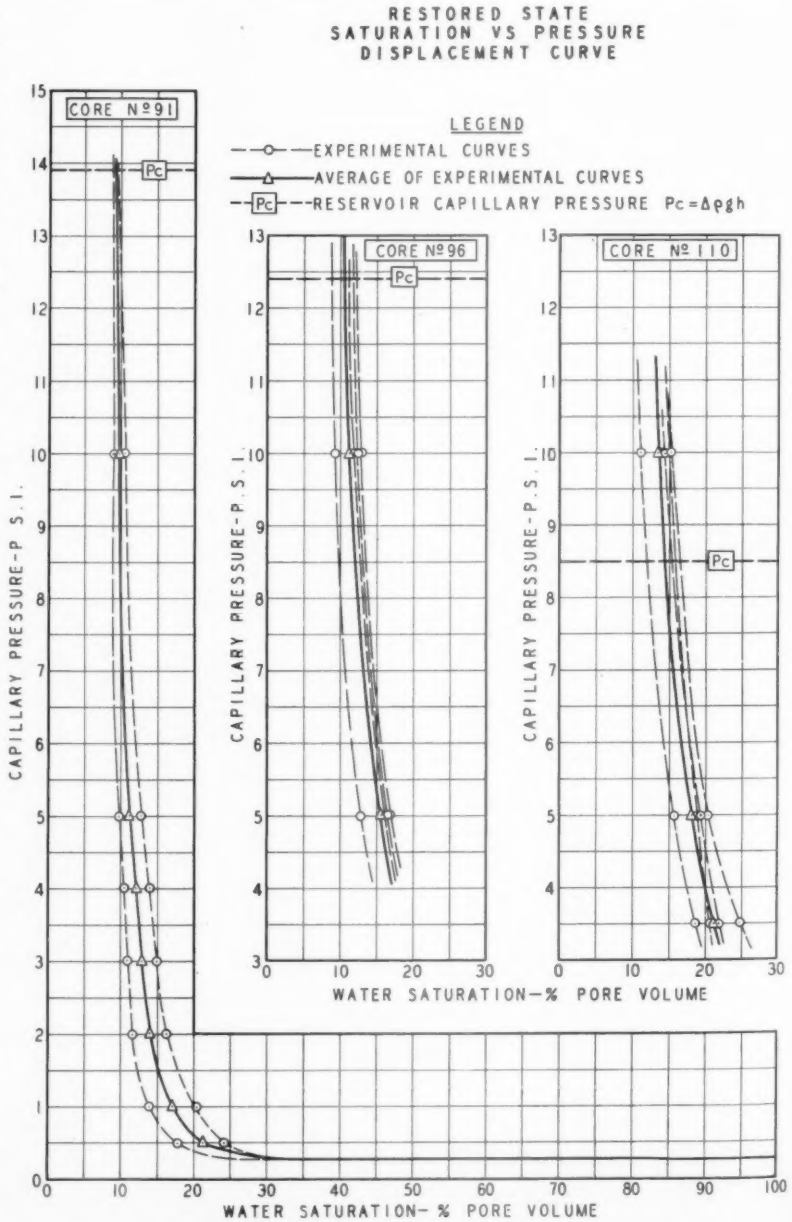


FIG. 6 — RESTORED STATE SATURATION VS. PRESSURE DISPLACEMENT CURVE.

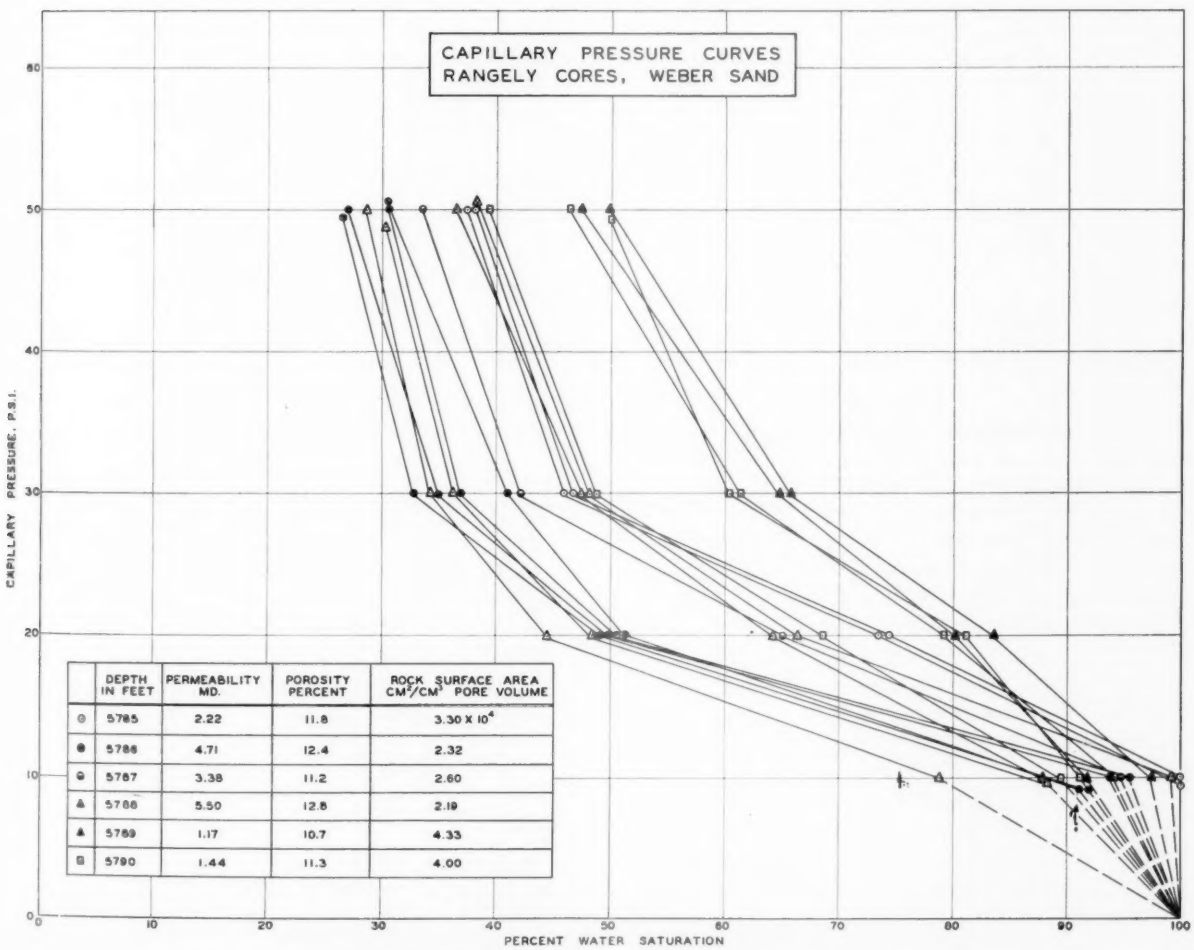
dependence of this relation on permeability, porosity, interfacial tension, and contact angle. The theoretical basis for this dependence and the technique of calculating capillary pressure curves are discussed in the next section. In each of the family of capillary pressure curves shown in Fig. 5 three of the above listed parameters are held constant and the fourth is varied over a reasonable range to show the relative effect of this fourth variable. It is observed that small deviations of the contact angle from zero only slightly displaces the curve; that considerable variation in porosity can be tolerated without seriously displacing the curve; and that independent variation of interfacial tension or core permeability produces considerable distortion of the capillary pressure curves.

THE CAPILLARY RETENTION RELATION

Employment of apparatus such as that illustrated in Fig. 2 has been the common method of experimentally evaluating capillary pressure behavior. The following theoretical development based on the concept of capillary retention suggests the possibility of another approach using the multi-core apparatus illustrated in Fig. 3. Leverett in two of his theoretical papers[17,21] developed the semi-emperical relation

$$j(S_w) = \frac{P_c}{\Upsilon}\left(\frac{K}{f}\right)^{\frac{1}{2}} \quad . \quad . \quad (1)$$

which he accepted because it was indicated by dimensional analysis and was supported by experimental data. Here $j(S_w)$ is a dimensionless function of the wetting phase saturation, termed the "capillary pressure function". P_c is the capillary pressure which Eq. (1) shows as being proportional to $j(S_w)$ and to the interfacial tension, Υ, and inversely proportional to the square root of the permeability-porosity ratio, $(K/f)^{\frac{1}{2}}$. This term, $(K/f)^{\frac{1}{2}}$, according to derivation from the Poiseuille and Darcy equations, can be shown to be equal to the "average pore radius" of the porous system being studied. Hence, there is theoretical justification for Eq. (1) since it conforms to basic concepts of capillarity as defined by Eq. (2). Leverett's data showed that a plot of the capillary function, $j(S_w)$, versus saturation of the wetting phase, S_w, yielded a unique curve which described in an adequate manner the capillary retention of wetting liquid existing in the clean, unconsolidated sands studied, when capil-



	DEPTH IN FEET	PERMEABILITY MD.	POROSITY PERCENT	ROCK SURFACE AREA CM^2/CM^3 PORE VOLUME
○	5785	2.22	11.8	3.30×10^4
●	5786	4.71	12.4	2.32
◎	5787	3.38	11.2	2.60
△	5788	5.50	12.8	2.19
▲	5789	1.17	10.7	4.33
□	5790	1.44	11.3	4.00

FIG. 7 — CAPILLARY PRESSURE CURVES RANGELY CORES, WEBER SAND

lary forces were balanced by gravitational forces (static equilibrium condition). A re-plot of Leverett's average data is shown in Fig. 8, along with data obtained on a number of consolidated systems according to the method presented in this paper. The theoretical aspects of this data plot are discussed below.

Starting from the basic concept of capillary rise in circular tubes, where

$$P_c = Dgh = \frac{2\tau}{r} \quad . \ . \ . \quad (2)$$

(complete wetting is assumed for the purpose of simplicity, that is, the contact angle, θ, is zero), Carman[22] has shown how an evaluation of capillary rise in other more complex systems, such as random-packed, non-spherical sand systems, can be made by assuming that twice the "hydraulic radius" is suitable value to use for the radius, r, in Eq. (2). Since this "hydraulic radius" is defined as the ratio of porosity, f, to surface area in units of bulk volume, A, Eq. (3) can be derived where h indicates the height of capillary rise, D is the density difference between fluid phases, and g is the gravitational constant.

$$\frac{P_c}{\tau} = \frac{Dgh}{\tau} = \frac{A}{f} \quad . \ . \ . \quad (3)$$

Carman studied clean unconsolidated sand systems similar to those used by Leverett (loc. cit.) and seemed to obtain experimental confirmation to support his theoretical argument. The close connection between the work of Carman and Leverett is evident by considering the Kozeny equation[23,24] which expresses specific surface area in terms of permeability and porosity and other constants (and which is rearranged here to conform with the units and dimensions of the other equations in this paper).

$$A = f\left(\frac{f}{K}\right)^{1/2}\left(\frac{1}{k}\right)^{1/2} \quad . \ . \quad (4)$$

Here, k is the numerical (rock textural) constant which makes the Kozeny equation describe streamline motion through granular beds. This equation can be combined with Eq. (3) to yield an expression similar to Eq. (1). Thus, when S_w equals unity

$$\frac{P_T}{\tau}\left(\frac{K}{f}\right)^{1/2} = \left(\frac{1}{k}\right)^{1/2} \quad . \ . \quad (5)$$

where P_T is the threshold pressure, defined as

$$\lim_{S_w \to 1} \quad P_c = P_T$$

By replacing P_c by P_T in Eq. (3), a possible minimum value for A/f is obtained. Accordingly,

$$\lim_{S_w \to 1} \quad j(S_w) = \left(\frac{1}{k}\right)^{1/2}_{\text{minimum}} \quad . \ . \quad (6)$$

In this manner a numerical interpretation is given to the limiting value of the capillary pressure function. Eq. (6) shows the limiting value of the $j(S_w)$ function to indicate a minimum value of the square root of the reciprocal Kozeny constant, k. Carman[25,26], Fowler and Hertel[27], and others have evaluated this constant, k, as it applies to a variety of unconsolidated systems by an independent method, and find experimentally that it is approximately 5. From basic capillarity as it applies to the geometry of the system it can be shown that for ideal systems (viz. regular packed, uniform spheres) k is equal to 5.

The replot of Leverett's data in Fig. 8 shows 0.42 to be the limiting $j(S_w)$ value, or according to Eq. (6), k equals 5.7. This value compared with the Fowler and Hertel (loc. cit.) have obtained a value of 5.5 for similar systems. Table

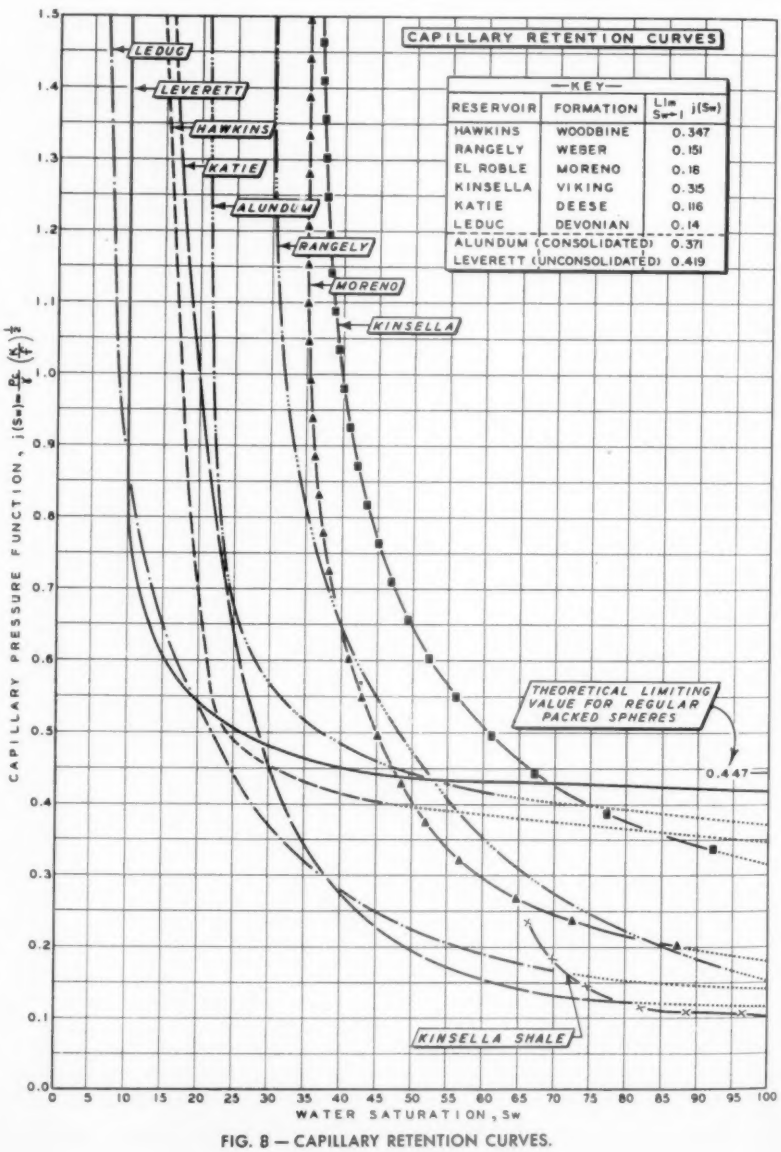


FIG. 8 — CAPILLARY RETENTION CURVES.

I (Page 137) correlates the limiting $j(S_w)$ values observed in Fig. 8 with the character of the porous system to *indicate qualitatively* a relationship between rock properties and deviations from ideal behavior.

Table II obtained from the analysis of data on several cores from the same reservoir presents evidence that the deviation of limiting values for $j(S_w)$ from 0.447 (ideal case) is related to the presence of fine interstial material (in this case clays).

It is assumed in Table II that weight per cent fines as determined in grain sieve analysis is a rough measure of interstitial clays. However, these data should not be interpreted to mean that the presence of interstial clays is responsible entirely for deviations of limiting j values from the ideal value. It is probable that cementation, secondary alteration of pore character, as well as other factors will likewise cause deviations. All other factors being equal, it can be inferred that an increase in interstitial clay content will cause a corresponding decrease in the experimentally determined limiting j values.

TABLE II

Weight Pct. fine fraction (Sieve anal.)	Pct. Clay	Lim $j(S_w)$ $S_w \rightarrow 1$	k Values
5.1	—	0.17	35.0
5.7	5.9	0.18	31.2
5.9	5.7	0.21	23.0
8.9	8.5	0.08	155.0
11.6	—	0.05	400.0

Aside from the fact the threshold pressure P_T can be derived, and limiting values of the Kozeny constant, k, evaluated from the $j(S_w)$ versus S_w data plot, there are several other interesting applications possible. Fig. 9 is a capillary retention plot of the capillary pressure data shown in Fig. 7. It is observed that the similar capillary retention behavior of these argillaceous cores is not at once apparent in Fig. 7, nor was it anticipated by the statements of Leverett (loc. cit.) who suggested that interstitial clays would present an anomalous situation. Fig. 9, on the other hand, shows how the porosity-permeability compensation of the j-function treatment suitably corrects capillary pressure data to show the basic behavior character of the porous rock. Fig. 10 shows how the J-Curve reveals the character of a type of limestone, even though these cores had a scattered permeability-residual water saturation plot.

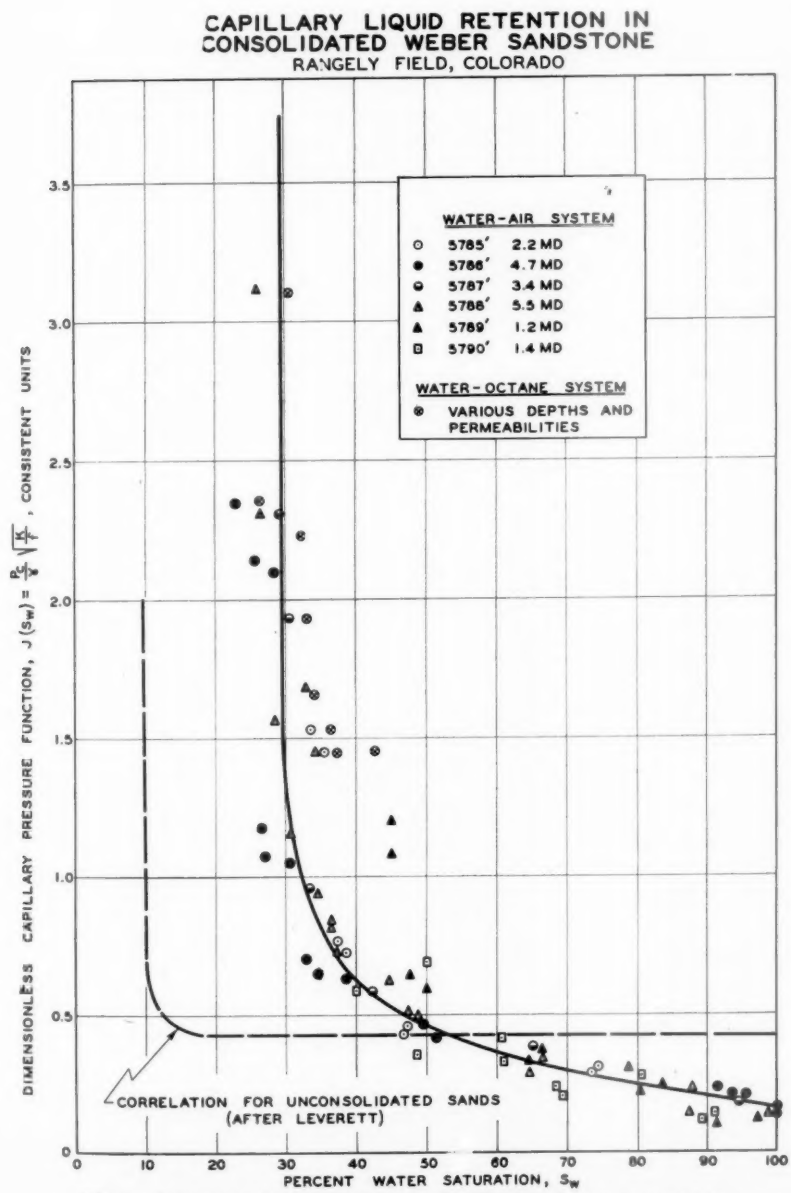


FIG. 9 — CAPILLARY LIQUID RETENTION IN CONSOLIDATED WEBER SANDSTONE.

USE OF NOMOGRAPH

Fig. 11 is a nomograph relating values for $j(S_w)$, P_c, or P_T, K, k, f, τ, to each other, such that any of these variables can be calculated by nomographic construction providing the others are known or assumed. The values for $j(S_w)$ plotted in Figs. 8, 9, and 10 were calculated in this manner and then associated with the proper wetting phase saturation values to yield these capillary retention curves. A more interesting application is to use this nomograph in the reverse process of calculating capillary pressure curves from capillary retention data. Thus, it is observed that once the capillary retention trend characterizing a given type of rock is obtained, values for capillary pressure can be related nomographically to $j(S_w)$ values, which are in turn related by the capillary retention curve to definite saturation, S_w, values. All that need be known (or assumed) are values for

permeability, porosity and interfacial tension. Fig. 5 has been presented above as a complete example of this calculation.

It is apparent that the multi-core apparatus described in the first part of this paper (Fig. 3) has special application in the derivation of calculated capillary pressure curves from capillary retention data plots. For example, if several cores from the same formation but differing in permeability, porosity, and other characteristics are assembled in the multi-core apparatus, in many instances sufficient data will be obtained to establish the capillary retention curve by merely applying a single displacing pressure to the apparatus and then measuring residual wetting phase saturations in the individual cores after static equilibrium has been attained. This is illustrated in Fig. 7 where saturations ranging between 45 and 85 per cent are observed to characterize this group of fifteen cores under conditions of 20 psi capillary pressure. There are enough data to establish part of the capillary retention curve presented in Fig. 8. Furthermore, the whole capillary pressure curve can be established for any of these cores if porosity, permeability, and interfacial tension are known.

The use of the nomograph entails first joining the porosity and interfacial tension values with a straight edge, producing a point of intersection on the multiplier scale. This point is then joined to the proper permeability value, producing another point of intersection on the

$$\tau\left(\frac{f}{K}\right)^{1/2}$$

scale. Finally, a series of straight lines through this latter point intersecting the other two scales of the nomograph will give values of capillary pressure, (P_c) which are related to corresponding values of $j(S_w)$. Employing the capillary retention curve, values for P_c then can be associated with values of S_w to produce calculated capillary pressure curves of the type illustrated in Figs. 5. Since considerable time is required to measure experimentally a capillary pressure curve, this multi-core method of calculating the capillary pressure relation permits considerable saving of experimental time. It is noted that these calculated curves deviate from experimental curves to the same degree that experimental data points deviate from the average trend when plotted on the capillary retention curve. In this connection, some deviation of individual values can be tolerated since the multiple core approach has been organized to reveal more about the capillary properties of the reservoir from which the core material was recovered, rather than to tell about the detailed anomalies in the properties of any particular core.

INTERPRETATION OF THE KOZENY RELATION, TORTUOSITY, AND SURFACE AREA

The Kozeny relation as stated in Eq. (4) can be given in a more explicit form. The actual streamline flow velocity through channels in a porous system is greater than the apparent velocity by virtue of the tortuous path which must be followed. Thus, the permeability may be expressed as

$$K = \frac{fm^2}{k_o}\left(\frac{L}{L_e}\right)^2 \text{(c.g.s. units)} \quad . \quad (7)$$

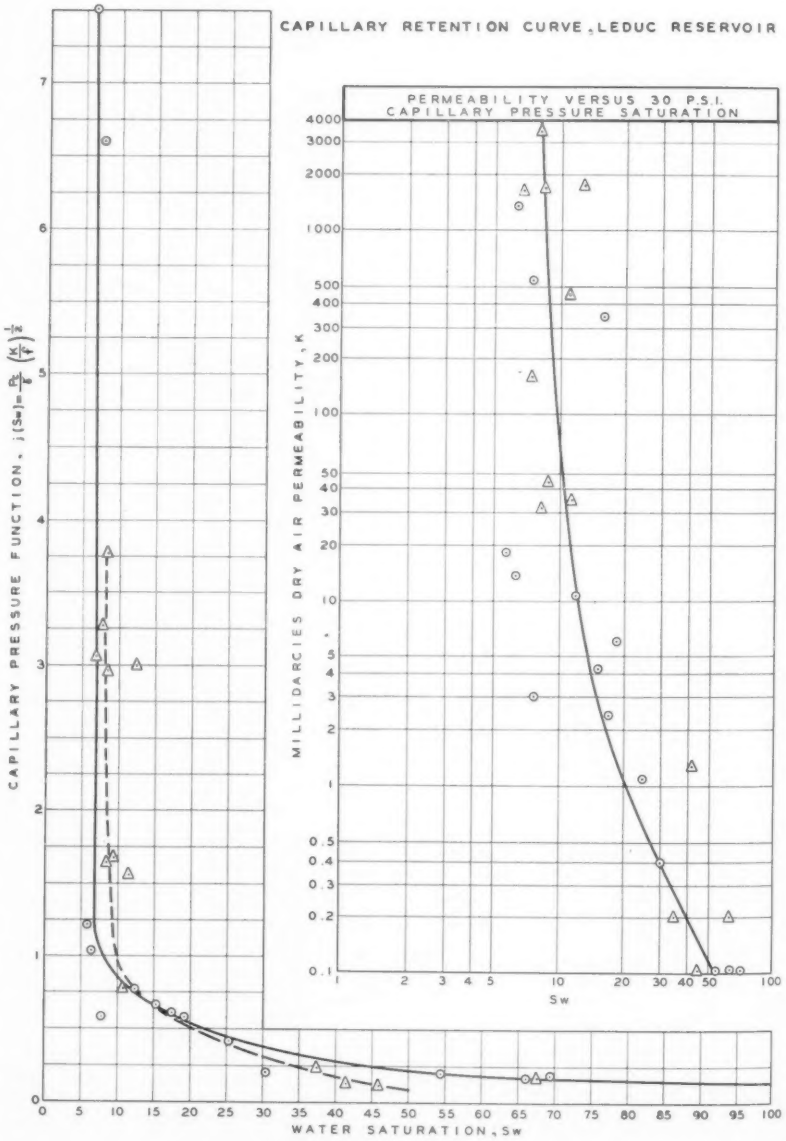
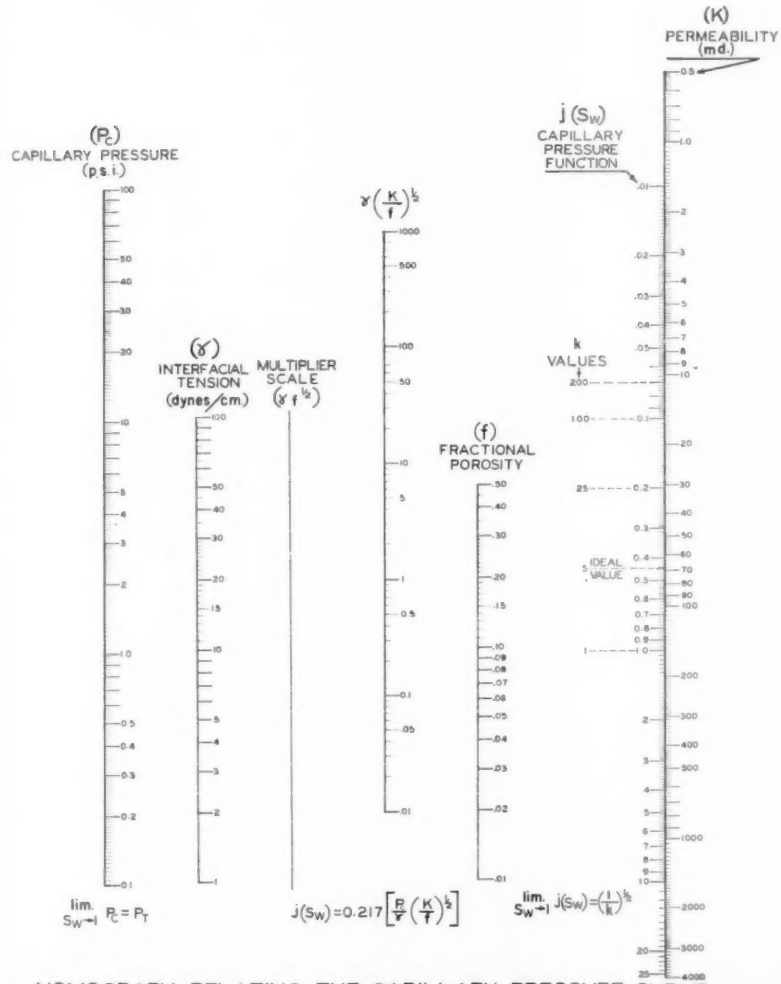

CAPILLARY RETENTION CURVE, LEDUC RESERVOIR
PERMEABILITY VERSUS 30 P.S.I. CAPILLARY PRESSURE SATURATION
CAPILLARY PRESSURE FUNCTION, $j(S_w)=\frac{P_c}{\sigma}\left(\frac{K}{\phi}\right)^{\frac{1}{2}}$
MILLIDARCIES DRY AIR PERMEABILITY, K
Sw
WATER SATURATION, Sw

FIG. 10 — CAPILLARY RETENTION CURVE, LEDUC RESERVOIR.

TABLE I*

Type Rock	Rock Character	$\lim_{S_w \to 1} j(S_w)$ Value	k Value	Permeability range, md.
Uniform pack spheres	Ideal system	0.447	5.	
Unconsolidated sand (Leverett)	Clean, random packed	0.42	5.7	50-2,000,000
Alundum synthetic cores	Sintered Alumina	0.37	7.2	50-1,500
Hawkins (Woodbine)	Clean Sandstone	0.35	8.2	2,000-6,000
Kinsella (Viking)	Fairly clean sand	0.31	10.5	500
El Roble (Moreno)	Argillaceous sand	0.18	31.2	5-500
Rangely (Weber)	Argillaceous bedded Sand	0.175	33.0	1-10
Leduc (Devonian)	Dolomitic Limestone	0.14	52.0	1-2,000
Katie (Deese)	Argillaceous Sand	0.12	70.5	50-250
Kinsella (Viking)	Shale with interbedded Sand	0.10	100.0	1-20

* Values for $\lim_{S_w \to 1} j(S_w)$ and k are indicated also in Fig. 8, 14, and 15 which occasionally differ from those reported in Table I. In general, the values reported in Table I are those which have been used in the calculations reported in this paper. They correspond to maxima in k.



NOMOGRAPH RELATING THE CAPILLARY PRESSURE CURVE TO THE CAPILLARY RETENTION CURVE

FIG. 11 — NOMOGRAPH RELATING THE CAPILLARY PRESSURE CURVE TO THE CAPILLARY RETENTION CURVE.

where m = mean hydraulic radius as previously defined
L = length of porous sample
L_a = actual length of path taken by fluid in traversing depth, L, of the porous bed
k_o = a constant in the general law of streamline motion through channels of uniform, but non-circular, cross-section

Carman (loc. cit.) shows that $k_o = 2$ as a very general average for many uniform systems, and Bartell and Osterhof[23] accept the value $\pi/2$ for the minimum La/L ratio so that a value for $k = 5$ is obtained. Actually, the tortuosity, T_1, of a porous system can be defined in terms of the $(La/L)^2$ function so that tortuosity,

$$T_1 = \left(\frac{L_a}{L}\right)^2 = \frac{k}{k_o} = \frac{k}{2} \quad . \quad . \quad (8)$$

(assuming $k_o = 2$). These relationships are of interest in defining the significance of the Kozeny constant, k.

Tables II and III suggest maximum values of tortuosity characterizing natural reservoir rock systems as high as $T_1 = 200$. This concept of tortuosity is useful, both from the standpoint of numerically evaluating the Kozeny constant, k, and from the standpoint of establishing another core analysis parameter related to the capillary character of porous systems.

The Kozeny equation (4) has been found useful to estimate interstitial surface area values for correlation purposes. Fig. 12 shows the trend which is observed when surface area values are plotted against connate water as determined by the capillary pressure method. The linearity of this curve suggests the possibility of inferring reservoir connate water character from porosity-permeability information (i.e. the variables appearing in the Kozeny equation) once the trend is established for a given type of formation. Leverett[17] originally called attention to the dependence of the capillary pressure curve on surface area considerations and the present paper relates both threshold pressures (Eq. 3) and irreducible interstitial water values (Fig. 12) that is, both ends of the drainage loop of the capillary pressure curve-to Kozeny calculated surface areas. Sullivan and Hertel[24] have stated in their review of this subject that the Kozeny equation has doubtful

significance when applied to consolidated systems, or to media characterized by bridging, agglomeration or channeling, since it is not certain how much of the surface is actually exposed to flow. From the standpoint of measuring true surface area this criticism may be justified although the usefulness of Kozeny surface areas for correlation purposes should not be overlooked. On the other hand, it has been shown in this paper that the Kozeny constant of proportionality (k) can be estimated by an independent method (Eq. (6) as it applies to consolidated systems; therefore it is probable that some compensation for the effects of consolidation, etc., are possible.

Table III is presented to illustrate the order of magnitude of the interstitial surface area for different types of porous media.

APPLICATION OF STATIC CAPILLARITY TO THE DYNAMIC PROBLEMS OF FLOW

For some time interest has been expressed in the possibility of obtaining relative permeability from capillary pressure data. The following development shows how the relative permeability to the wetting phase can be approximated at different saturations from capillary pressure data if certain assumptions are made.

Eq. (5) can be rearranged

$$K = f\left(\frac{1}{k}\right)\left(\frac{\Upsilon}{P_T}\right)^2 \quad . \quad . \quad . \quad (5a)$$

to show that the specific permeability, (K), may in a first approximation be proportional to the reciprocal Kozeny constant, (1/k), to the porosity, (f), and to the square of the interfacial tension-threshold pressure ratio, $(\Upsilon/P_T)^2$. In this expression complete wetting is assumed, and the cosine of theta is therefore one. Eq. (5a), as it has been deduced, applies to a porous system completely saturated with a wetting phase. Now, if it may be assumed that as the porous system is desaturated during a capillary pressure experiment, Eq. (5a) may be rewritten so that it continues to apply, then

$$K_E = f_E\left(\frac{1}{k}\right)\left(\frac{\Upsilon}{P_c}\right)^2 \quad . \quad . \quad . \quad (5b)$$

where (P_c) is the capillary pressure associated (on the capillary pressure diagram) with given values for the wetting phase saturation, S_w. K_E is the effective permeability to the wetting phase at saturation, S_w, f_E is the effective porosity defined as the volume of the wetting phase per unit of bulk volume.

That is, $f_E = f\ S_w$

therefore,

$$K_E = f\ S_w\left(\frac{1}{k}\right)\left(\frac{\Upsilon}{P_c}\right)^2 \quad . \quad . \quad (5c)$$

The justification for these equations (5b and 5c) depends on the argument that values for P_c obtained in a capillary pressure expermient may be regarded as equivalent to the threshold pressures of pores of a definite size. In other words, the capillary pressure at saturation, S_w, is actually a threshold pressure of the maximum sized pore which is completely filled under this condition of saturation, S_w. A further assumption is that the constant, k, appearing in Eqs. (5a), (5b), and (5c) is a unique constant which has the same value regardless of which pores in the system (or portions thereof) are being considered. This latter assumption is reasonable since, according to Eq. (8), the constant k may be defined as the product of a dimensionless pore shape factor and a pore orientation factor. That is, k is a function of pore configuration and not pore size.

Combining Eqs. (5a) and (5c) gives an expression for relative permeability of the wetting phase, (K_w).

$$K_w = S_w\left(\frac{P_T}{P_c}\right)^2 \quad . \quad . \quad . \quad . \quad . \quad (9)$$

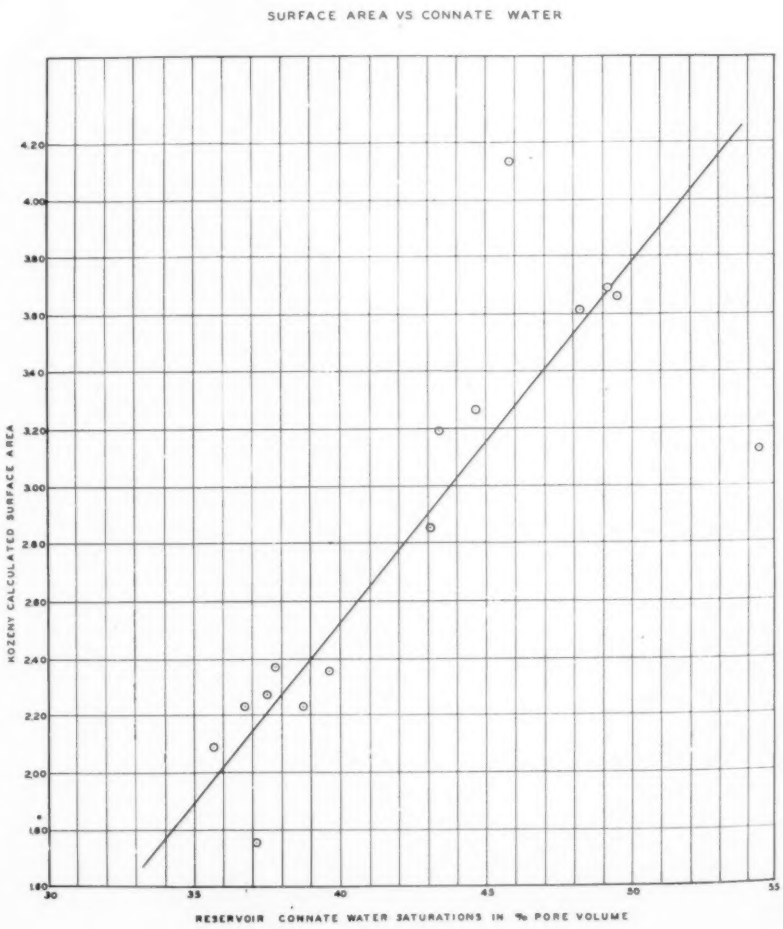


FIG. 12 — SURFACE AREA VS. CONNATE WATER.

Martinelli *et al*[36] recently have made an experimental study of the relative permeability characteristics of a capillary tube, and Fig. 13 illustrates the result they obtained. It is evident that their $K_w - S_w$ curve is predicted entirely by Eq. (9) since in the case of a capillary tube $P_c = P_T$ for all values of S_w so that $K_w = S_w$ (approximately) as shown in Fig. 13

Fig. 13 not only shows relative permeability curves obtained by previous workers[30,36] on capillary tube and unconsolidated sand systems, but it also illustrates a comparison of the K_w vs. S_w curves obtained by experiment and by theory (Eq. 9) as they apply to a consolidated sand core. Until more such direct comparisons can be made no speculation will be attempted to explain the discrepancy between theory and experiment. It is recognized that irreducible minimums are associated with the maximum saturation where the wetting phase has zero permeability, and that previous experimental work does not indicate consistently this condition. In this sense the calculated curve in Fig. 13 is more reasonable than the experimental curve, at least in the regions of low saturation.

In conclusion, it is pointed out that Eq. (9) predicts that the wetting phase relative permeability relation should be independent of rock and fluid properties (e.g. permeability, porosity, interfacial tension) as long as the group of cores being considered are characterized by the same capillary retention curve.

Thus, according to Eq. (9)

$$K_w = S_w\left(\frac{P_T}{P_c}\right)^2 = S_w\left(\frac{\lim_{S_w \to 1} j(S_w)}{j(S_w)}\right)^2 = \left(\frac{S_w}{k}\right)\left(\frac{1}{j(S_w)}\right)^2 . \quad (9a)$$

Eq. (9a) offers theoretical explanation to an experimental fact (previously observed in the cited reference) that ideal systems (e.g. capillary tube, regular packed sand, etc.) are characterized by higher K_w values associated with given S_w values than non-ideal systems (e.g. consolidated sands). Eq. (9a) shows that the system characterized by a low value of k will have a higher value of K_w than a system characterized by a high value of k. This condition is predicted by Eq. (9a) under conditions where the two systems being considered are further characterized by approximately the same capillary retention relation. It is shown in this paper that high values of k reflect non-ideal systems, and this supports the above conclusion made about the significance of Eq. (9a). Fig. 14 (offered to support this argument) has been obtained by plotting the capillary retention data shown in Fig. 8 in the way indicated by Eq. (9a). The various relative permeability curves obtained (with the exception of the curve for the Leduc limestone) are all oriented with respect to each other in the manner suggested by the above discussion, such that it may be concluded that this method of calculation qualitatively checks the cited experimentally observed trends.

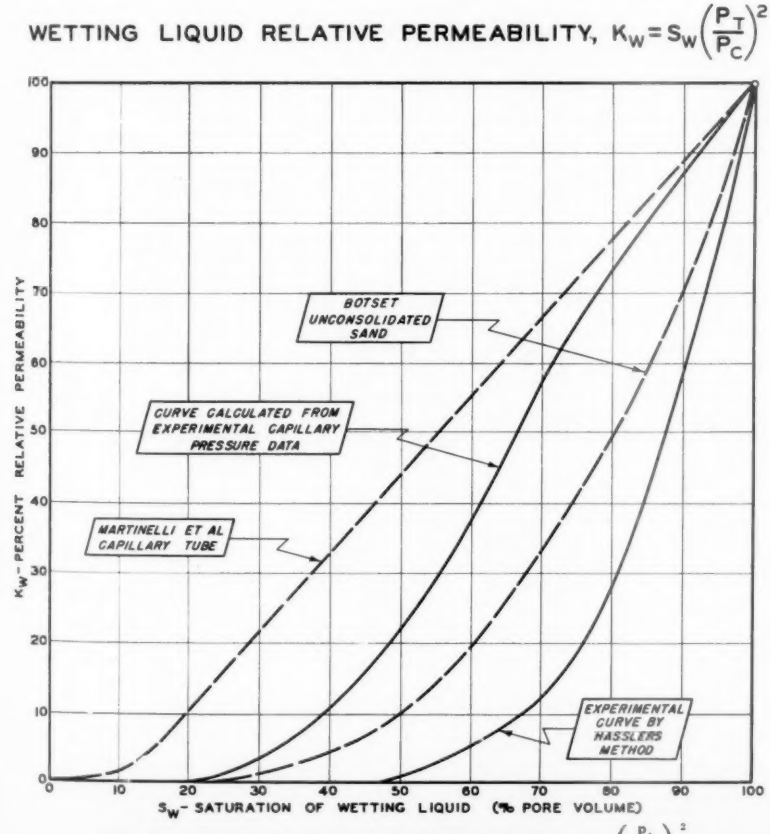


FIG. 13 — WETTING LIQUID RELATIVE PERMEABILITY, $K_w = S_w\left(\frac{P_t}{P_c}\right)^2$

UNIVERSAL CAPILLARY PHI-PSI RELATIONSHIPS

The following development was attempted to provide a universal relationship which would define the capillarity of any porous system.

The fundamental Kozeny relation (Eq. 4) can be written as

$$K = \frac{f}{k(A')^2} . \quad . \quad . \quad . \quad . \quad (4a)$$

where A' is now the interstitial surface area in cm^2 per cm^3 pore volume. If it is assumed as previously that Eq. (4a) can be extended over the whole saturation range, and by using Leverett's expression for interfacial surface area as given by

$$1/T \int_{S_w}^{1} P_c dS_w,$$

the following dimensionless function can be derived:

$$\phi = S_w\left[1 + k^{1/2}\int_{S_w}^{1} j(S_w)\, d\, S_w\right]^{-2} . \quad (10)$$

Consideration of equation (10) shows that the slope of ϕ versus S_w as S_w approaches unity is equal to 3. For the

special case of a capillary tube it can be shown that

$$\phi = \frac{S_w}{(2 - S_w)^2} \quad . \quad . \quad . \quad (11)$$

where the slope of ϕ is equal to 3 as S_w approaches unity and equal to 0.25 as S_w becomes zero.

Fig. 15 (Phi relation) shows a plot of ϕ versus S_w as it applies to a capillary tube according to Eq. (11). Also shown for comparison are similar plots and they apply to other porous systems according to Eq. (10). It is observed that all systems show limiting slopes of 3 as predicted.

It has been observed experimentally that $j(S_w)$ vs. S_w tends to become vertical as S_w approaches an "irreducible minimum" value. This minimum might be labeled, S_o, and defined as that value of S_w for which ϕ becomes vanishingly small. If the water is being displaced by oil, there is evidence that an S_o exists for which ϕ actually becomes zero.

This behavior suggests that a modified relation can be developed by defining a new variable, S, the saturation function

$$S = \frac{(S_w - S_o)}{(1 - S_o)} \quad . \quad . \quad . \quad (12)$$

After the manner of equation (10), it is now possible to write

$$\Psi = S\left[1 + k^{1/2} \int_S^1 j(S)\ dS\right]^{-2}$$

or in terms of more easily evaluated experimental quantities

$$\Psi = S\left[1 + \frac{k^{1/2}}{(1-S_o)} \int_{S_w}^1 j(S_w)\, d\, S_w\right]^{-2} \quad (13)$$

Fig. 15 also shows a plot of Ψ versus S as it applied to the porous systems discussed above.

CONCLUSIONS

The object of the work reported in this paper is to call attention to the theoretical aspects of capillary behavior which yield a characterization of the capillary properties of a porous system, such as petroleum reservoir rock. This permits a more exact description of fluid behavior in porous media. Considerations of pore configuration, rock surface properties, and fluid properties contribute to this characterization. Although, certain of these factors can be independently measured, this paper attempts to show that the capillary pressure test provides a measurement of the combined effect of all of these factors. For instance, the data obtained from the capillary pressure test can be interpreted to reflect the distribution, orientation, shape, and tortuosity of pores; the interfacial and interstitial surface area; and finally relative permeability to the wetting phase. The new experimental techniques and computation aids described in this paper have been shown to be useful for this work.

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NOMENCLATURE AND DIMENSIONS OF VARIABLES

Symbol	Meaning	Dimensions
a	Effective Interstitial Surface Area (Area per unit of pore volume)	1/L
A'	Interstitial Specific Surface Area (Area per unit of pore volume)	1/L
A	Interstitial Specific Surface Area (Area per unit of bulk volume)	1/L
A_I	Interfacial Specific Surface Area (Area per unit of pore volume)	1/L
D	Density difference between fluids	M/L^3
f_E	Effective fractional porosity	None
K_E	Effective permeability	L^2
f	Fractional porosity	None
g	Gravitational constant	L/T^2
Υ	Interfacial tension	M/T^2
h	Height of fluid interface above level of zero curvature	L
$j(S_w)$	Capillary pressure function	None

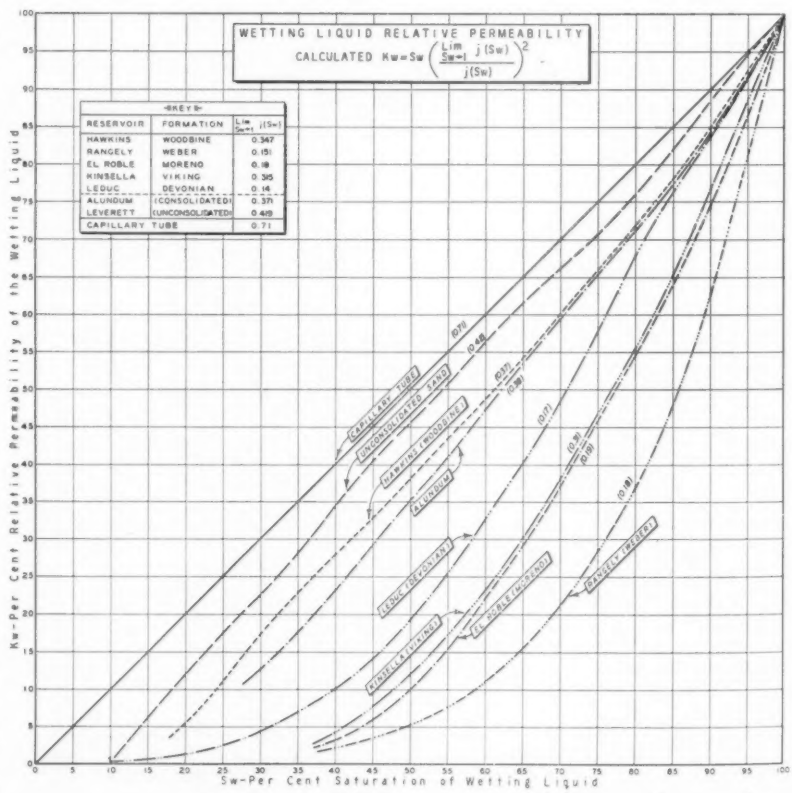
WETTING LIQUID RELATIVE PERMEABILITY
CALCULATED Kw=Sw (lim Sw→1 j(Sw) / j(Sw))²
KEY
RESERVOIR | FORMATION | lim Sw→1 j(Sw)
HAWKINS | WOODBINE | 0.347
RANGELY | WEBER | 0.151
EL ROBLE | MORENO | 0.18
KINSELLA | VIKING | 0.395
LEDUC | DEVONIAN | 0.14
ALUNDUM | (CONSOLIDATED) | 0.371
LEVERETT | (UNCONSOLIDATED) | 0.419
CAPILLARY TUBE | | 0.71
Kw-Per Cent Relative Permeability of the Wetting Liquid
Sw-Per Cent Saturation of Wetting Liquid

FIG. 14 — WETTING LIQUID RELATIVE PERMEABILITY CALCULATED $K_w = S_w \left(\frac{\lim_{S_w \to 1} j(S_w)}{j(S_w)}\right)^2$

TABLE III

Core Description	P_T Threshold Pressure (psi)	Interfacial Tension (dynes/cm.)	$A'^{(1)}$ Surface Area (cm^2 per cm^3 of pore volume)	f Porosity (fractional)	K Permeability (md)	$\lim_{S_w \to 1} j(S_w) = \left(\frac{1}{k}\right)^{1/2}$ (dimensionless)
Weber Sandstone	16.7	70	1.65×10^4	0.118	2.1	0.20
" "	12.3	70	1.21	0.119	2.4	0.22
" "	8.1	70	0.80	0.124	4.4	0.17
" "	8.5	70	0.84	0.125	5.9	0.18
" "	6.5	70	0.64	0.112	3.4	0.17
" "	11.3	70	1.11	0.122	2.9	0.15
" "	7.4	70	0.73	0.132	5.9	0.17
" "	10.5	70	1.03	0.136	11.1	0.27
" "	7.0	70	0.69	0.121	2.2	0.07
" "	8.5	70	0.84	0.111	1.3	0.10
Viking Sandstone	3.7	70	0.36	0.17	10.0	0.10
"	1.5	70	0.15	0.22	650.	0.31
Unconsolidated Sand (After Leverett)	0.6	70	0.059	0.39	1.75×10^4	0.42
Alundum	2.0	70	0.20	0.24	208.	0.38
"	0.8	20	0.23	0.24	208.	0.38
Deese Sandstone	1.0	70	0.99	0.15	253.	0.16

k	Constant in general law of streamline motion through granular beds	None
k_o	Constant in general law of streamline motion through channels of uniform cross section	None
K	Specific permeability	L^2
K_w	Relative permeability of wetting fluid	None
L	Apparent length of pore (actual length of core)	L
L_a	Actual length of pore	L
m	Mean hydraulic radius	L
P_c	Capillary Pressure	M/LT^2
P_T	Threshold pressure	M/LT^2
r	Interstitial pore radius	L
$\bar{r}$	Average interstitial pore radius	L
S	Saturation Function	None
S_w	Fractional wetting phase saturation (per units of pore volume)	None
S_o	"Irreducible" wetting phase saturation	None
T_1	Tortuosity	None
θ	Contact angle	Degrees
ϕ	Phi Function	None
Ψ	Psi Function	None

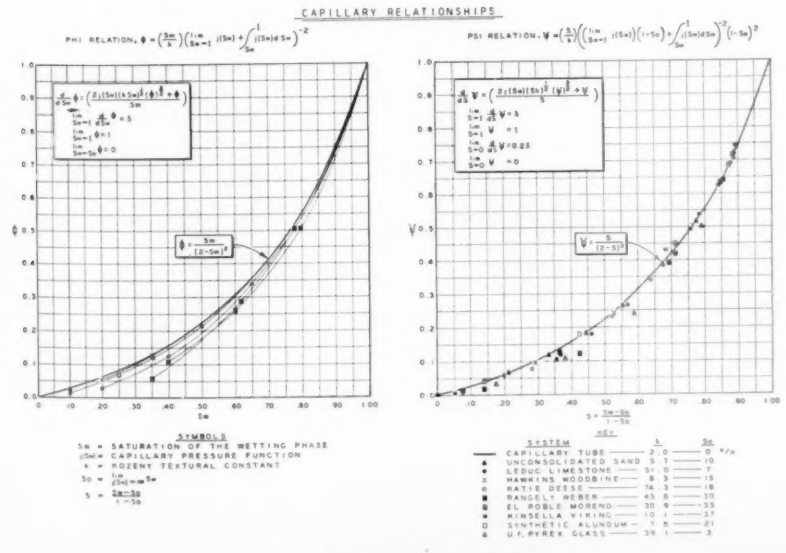

FIG. 15 — CAPILLARY RELATIONSHIPS.

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